SYSTEMS ENGINEERING
Research Center

A US Department of Defense University Affiliated Research Center

SERC 2014-2018 Technical Plan: 2016 Update

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EXECUTIVE SUMMARY

This Systems Engineering Research Center (SERC) 2014-2018 Technical Plan aligns the SERC Vision and Research Strategy with the Sponsor's Core funding priorities. It describes the SERC Vision, the Sponsor's needs, and the SERC's response to these needs, supported by research in *Enterprises and Systems of Systems* (ESOS), *Trusted Systems* (TS), *Systems Engineering and Systems Management Transformation* (SEMT) and *Human Capital Development* (HCD). A Grand Challenge statement is presented for each of these four research areas, along with a strategy to address it. Eleven research programs have been identified to support this strategy. Research projects are then presented which support each of these programs, consisting of existing and anticipated future projects.

This 2016 update describes progress since the Assistant Secretary of Defense for Research and Engineering approved the original SERC Technical Plan in October 2013 and annual Core funding was appropriated to match the Technical Plan. In this update, the Grand Challenges remain virtually unchanged, with the focus being updates to the research programs and other elements in the plan. In addition, this update includes much greater transition planning information than did the original version. The next Technical Plan update in two years will address changes to the Grand Challenges and research strategies, and will be used to support the Department of Defense's (DoD's) 5-year comprehensive review of the SERC.

More than two-dozen projects have been executed since the original Technical Plan was published, some to completion, others still ongoing. These projects have been delivering methods, processes, and tools (MPTs) in each of the four research areas that define the SERC research portfolio. Transition has also been ongoing and growing, with many acquisition programs and defense organizations piloting and adopting SERC MPTs as those MPTs have matured. Since October 2013, when the SERC began executing this plan, SERC researchers have delivered more than 110 papers and technical reports, and prototype software implementations of their methods and processes. Equally important, SERC collaboration and infrastructure have grown significantly, as reflected in the new SERC Innovation and Demonstration Lab, where projects can demonstrate their research both individually and coordinated across projects.

The grand challenges the SERC is addressing are:

> ESOS - *Create the foundational SE principles and develop the appropriate MPTs to enable the DoD and its partners to model (architect, design, analyze), acquire, evolve (operate, maintain, monitor) and verify complex enterprises and systems of systems to generate affordable and overwhelming competitive advantage over its current and future adversaries.*

> TS - *Achieve much higher levels of system trust by applying the systems approach to achieving system assurance and trust for the increasingly complex, dynamic, cyber-physical-human net-centric systems and systems of systems of the future.*

> SEMT - *Transform the DoD community's systems engineering and management methods, processes, tools and practices to enable much more rapid, concurrent, flexible, scalable definition and analysis of the increasingly complex, dynamic, multi-stakeholder, cyber-physical-human DoD systems and systems of systems of the future.*

HCD - *Discover how to dramatically accelerate the professional development of highly capable systems engineers and technical leaders in DoD and the defense industrial base and determine how to sustainably implement those discoveries.*

Although these challenges will not be fully addressed in the five-year timeline of this Technical Plan, progress is now apparent. For example, research efforts on Trusted Systems have yielded a promising new way to protect cyber-physical systems from cyber-attacks and have demonstrated the utility of that approach on unmanned vehicles. Research projects advancing our understanding of technical leadership, of how to accelerate maturation of systems engineers, and of what enables systems engineers to be effective have yielded new MPTs, courses, theories, and supporting software that are in their inaugural applications in government and industry. Further examples of progress are described in Section 5 for each ongoing project.

The SERC, guided by this Technical Plan, will deliver the greatest impact for DoD and the Intelligence Community (IC) by:

1. *Conducting* long-term research that makes significant progress on the grand challenges
2. *Transitioning* that research into practice within DoD, the IC, defense industrial base, and other federal agencies; and by developing more powerful ways to facilitate such transition
3. *Amplifying* sponsor resources by forging relationships with other organizations that become partners, contributing their resources and energy to the SERC and adopting SERC research
4. *Strengthening* the existing SERC culture, mechanisms and focus on collaboration
5. *Instituting* new approaches to educate future systems engineers and engineers that leverage the full strength and diversity of the collaboration

The strategy described in this Technical Plan embraces these principles by which to operate. For example, each existing Core-funded project has been receiving an initial funding level throughout 2014 and 2015, which will be reduced by approximately 20% per annum through the end of 2018. That reduction incentivizes Principal Investigators (PIs) to seek complementary funding from non-Core sources. Core funds freed up through this strategy accumulate in an investment pool that funds new programs and projects. Besides $14.722M previously spent on projects that became Core funded in 2014, the SERC was awarded more than $10M in 2008-2013 on projects that completed. Projects that completed prior to 2014 are not addressed in this plan.

1 SERC VISION

In the original Technical Plan published in 2013, the vision for the SERC *at the end of 20*18 was stated as:

- IMPACT: The SERC has indeed become the go-to place for high-quality SE research and exploratory development. Its research is widely applied in DoD and the defense industrial base with tangible impact affecting billions of dollars of acquisitions; its research results are woven into the curricula of dozens of university programs (including many outside the set of SERC Collaborators) that are educating thousands of students.

- TOP 25: The SERC includes ten of the US News and World Report (USNWR) top-25 Industrial/Manufacturing/Systems Engineering departments.

- STUDENTS: SERC Collaborators graduate over half of the US MS-SE and PhD-SE graduates per year. Many PhD graduates join other SERC universities as faculty or staff, significantly increasing the breadth and depth of research collaborations. Collaborators attract and educate the best students, drawn from current DoD and defense industrial base employees and from those who are attracted to systems engineering by the vigor and quality of Collaborator educational programs.

- LEADERSHIP: The SERC provides much of the leadership in SE-related professional societies, increasing collaboration among them. It continues to operate and grow the Conference on Systems Engineering Research as the premier SE research conference, along with feeding its papers into the leading SE-related journals.

- KNOWLEDGE: The SERC operates the world's largest and most-visited SE research website, including the largest and best-organized SE research experience base. It continues to provide leadership in evolving the SE Body of Knowledge. It runs the most widely attended and highest-rated SE webcast series.

- SCALE: The SERC has become a $20M/year enterprise: $5M of Core funding from ASD(R&E); $5M from other sponsors in the DoD/IC; $5M to apply research results in pilots with DoD operational organizations; and $5M in research and pilots from outside of DoD. Thus, each $1 of Core funding attracts an additional $3 of outside funding.

Over the past two years, incremental progress towards that vision includes:

- IMPACT: Although its footprint is still small, SERC research is being used in all Services, in the defense industrial base, and in academia – and that research use is steadily growing. For example, the Marines are using SERC-developed tools for tradespace analysis and systems portfolio analysis; the Navy is adopting SERC model-based systems engineering techniques; the Air Force is applying SERC cost modeling approaches to manage complex systems; both the Army and Defense Acquisition University are applying SERC approaches to growing technical leaders; several defense contractors are applying research on how to improve the effectiveness of their systems engineers; and many universities have adopted SERC developed approaches to weave systems thinking and systems engineering into engineering capstone projects. The adoption of SERC technology is expected to grow significantly over the next three years, primarily as a result of the SERC's greater focus on transition and because the SERC has an ever expanding portfolio of maturing research available to early adopters.

- TOP 25: The SERC Collaborator membership is proving to be more stable than anticipated when the Technical Plan was originally written in 2013. Eight SERC Collaborators are in the top 25 in the 2015 USNWR rankings for Industrial/Manufacturing/Systems Engineering programs.

- STUDENTS: During this coming year, the SERC will begin to collect data to measure progress against this aspect of its vision.

- LEADERSHIP: Over the past two years, faculty members from SERC Collaborator universities have played key roles within the International Council on Systems Engineering (INCOSE), the Accreditation Board for Engineering and Technology (ABET), the American Institute of Aeronautics and Astronautics (AIAA), and other professional societies; e.g., one Stevens professor is a member of the INCOSE Board of Directors, a Massachusetts Institute of Technology professor become Editor-in-Chief of the Systems Engineering Journal and a Georgia Tech professor become the Editor-in-Chief of the Journal of Enterprise Transformation.

- KNOWLEDGE: Last year the SERC launched a new website which provides a much improved platform to host and disseminate important knowledge about systems engineering and about SERC research. In 2016 the SERC will begin offering webcasts on its research and related topics. The SERC is one of the three organizations sponsoring the Systems Engineering Body of Knowledge, which has become one of the most prominent online source of information about systems engineering – http://www.sebokwiki.org/ averages almost 20,000 visitors monthly.

- SCALE: During government FY 2014, SERC awards totaled approximately $10M, including $5M in Core funding. Growing total awards to $20M in 2018 will be challenging, but is certainly feasible.

2 SPONSOR NEEDS

The outlook on SE needs for 2014-2018 might best be summed up in this statement from the INCOSE SE Vision 2025 report[1]: "Large and complex engineered systems are key to addressing [engineering] Grand Challenges and satisfying human and social needs that are physical, psychological, economic and cultural. However, these systems must be embedded in the prevailing social, physical, cultural and economic environment, and the technologies applied to system solutions must be tailored to the relevant local or regional capabilities and resources. Full lifecycle analyses and safe, robust and sustainable implementation approaches, along with stable governance environments are enablers for successful system solutions." We have entered an era of great system complexity, rapid technological change, growing resource stress, and societal systems that are both enabled and impacted by advancing engineered systems. Consideration for the system as an enterprise and system of systems must be a core part of systems engineering. There are increasing calls from all systems stakeholders for foundational tools that reflect the human, organizational, and societal aspects of engineered systems. These foundations must inform future research in systems engineering. MPTs that consider the system in use, and as a construct of a large development enterprise, are needed to strengthen future decision-making. The underlying challenges of our sponsor base rest on critical infrastructures that must be efficient, resilient, safe and secure, for which there is an increasing movement toward cyber-physical infrastructures and machine automation, with lifecycle considerations of sustainable resource use.

These foundations are pervasive in the needs of our DoD and IC sponsors. On April 9, 2015, Undersecretary of Defense for Acquisition, Technology & Logistics (USD (AT&L)) Frank Kendall introduced the third in a series of DoD Better Buying Power initiatives (BBP). BBP3.0, "Achieving Dominant Capabilities through Technical Excellence and Innovation," places a renewed emphasis on the effectiveness of DoD research and development activities including science and technology, system development, experimentation and prototyping, full-scale development, and technology insertion into fielded products[2]. The needs for new and evolving SE MPTs are reflected in a number of BBP3.0 initiatives, highlighted as follows:

- Improve decision makers' ability to understand and mitigate technical risk
- Increase the use of prototyping and experimentation
- Emphasize technology insertion and refresh in program planning
- Use Modular Open Systems Architecture to stimulate innovation
- Strengthen Cybersecurity throughout the program lifecycle
- Anticipate and plan for responsive and emerging threats by building stronger partnerships of acquisition, requirements, and intelligence communities
- Reduce cycle times while ensuring sound investments
- Improve the return on investment in DoD laboratories
- Increase the productivity of Independent Research and Development and Corporate Research and Development
- Strengthen organic engineering capabilities
- Increase DoD support for Science, Technology, Engineering, and Math (STEM) education

[1] See http://www.incose.org/docs/default-source/aboutse/se-vision-2025.pdf?sfvrsn=4.
[2] See http://bbp.dau.mil.

BBP3.0 reflects a call for much stronger integration of technology and its use, better tradespace understanding and decision-making, modular architectures and much better knowledge management, and consideration of cyber and physical interaction. A primary BBP3.0 research area of focus is supported by the DoD Engineered Resilient Systems (ERS) science and technology program[3] and by related SERC SEMT research. ERS key desired capabilities include tradespace tools and analytics for improved decision making, assessment of technical and program options, requirements analysis and generation, rapid generation of alternatives, as well as virtual prototyping and experimentation. ERS also includes development requirements for collaborative knowledge management and government managed modeling and simulation capabilities. Longer-range capabilities include systems architectures and concepts of operations (CONOPs), as well as lifecycle modeling and intellectual property management.

System Security Engineering remains a further strong area of focus for software-intensive system development, cyber-physical capabilities, and to address the need for much higher levels of system trust that are required as systems become increasingly capable and critical. System security engineering and risk-based frameworks for trust have become a core SE need for every system, whether open or restricted. The risk-based approach is evidenced with a major sponsor shift to the National Institute of Standards and Technology's (NIST's) Risk Management Framework requirements for government systems[4], and will lead to a need for research in full lifecycle approaches that increase system trust in design, reflect the human elements of the system, and provide sustainable approaches reflecting emergent properties of the system as a whole. The DoD released its new cyber strategy in 2015[5], recognizing both our commitment to "an open, secure, interoperable, and reliable internet" and that "the increased use of cyberattacks as a political instrument reflects a dangerous trend in international relations." Our DoD and IC sponsors are critically dependent on the successful defense of both DoD networks and systems and the US critical infrastructure from cyberattacks. This can be captured in an enterprise view reflecting information sharing and coordination, public and private integration of security and trust, and global alliances. Emerging SE challenges include recognition of the cyber mission in system CONOPs, convergence of enterprise and mission architecture frameworks, integration of human cyber operators in system requirements, technical and enterprise risk management approaches, resilient system-of-systems architectures for information and operations, and rapid integration of commercial innovation into defense systems.

As captured through DoD's Reliance 21 framework and related Service and other activities[6], reliable autonomy will be enabled in part by SE tools that balance human oversight of autonomous systems with appropriate autonomy and man-machine interaction. Such tools are needed to help autonomous systems safely accomplish complex tasks in all environments. This includes new MPTs for test and evaluation of autonomous behaviors and decisions. Human interaction that is intelligent, adaptive, and intuitive will require much greater integration of MPTs that blend human and machine workflows. This will support man-machine teaming but will also benefit all engineered systems. SE MPTs that support massive data architectures and alignment of data intensive algorithms with appropriate CONOPs must also be developed.

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[3] See http://www.dtic.mil/ndia/2014system/16903WedTrack2Holland.pdf.
[4] See http://csrc.nist.gov/publications/nistpubs/800-37-rev1/sp800-37-rev1-final.pdf.
[5] See http://www.defense.gov/News/Special-Reports/0415_Cyber-Strategy.
[6] See http://www.acq.osd.mil/chieftechnologist/reliance21.html.

The complexities of future systems will only increase the need for development of complex SE skills and knowledge, and the critical role of leadership and management skills at the core of the systems disciplines. INCOSE's SE Vision 2025 lists the following core systems engineering skills as key to future SE: domain specific application and technical knowledge, full lifecycle system experience, systems engineering foundations, systems and specialty engineering methods, technical leadership, socio-technical competency, and software based tools. SE Vision 2025 also notes that systems engineering skills are not just for systems engineers, but rather they are important for all engineers. In addition, all systems decision makers should have experience in systems thinking. Strong core STEM education and systems thinking introduced early in schools are needed to build the foundation of future systems engineers. This starts with stronger organic skills in systems and other engineering foundations. SE education must be complemented by effective leadership and management development. SE is a lifelong learning process that builds from technical depth, breadth of experience and knowledge, and strong leadership and communication. SE research will develop the tools for managing complexity, but also must develop the education programs that support effective analyses and decision making of those who will use them.

3 SERC RESPONSE TO SPONSOR NEEDS

The SERC actively manages its research portfolio, looking for and nurturing synergies between projects. The SERC works with its sponsor to identify projects that can have greater impact on DoD's strategic SE research needs. One such approach is the New Project Incubator, described in Section 6, in which SERC Collaborators propose new research ideas, with the most promising projects being given limited funds to support their early development.

Long-term project funding has been especially evident since 2012, when the majority of new funding began being spent on multi-year higher-impact projects. Most projects are now being conceived and proposed as multi-phase, multi-year efforts; for example, the *Experience Accelerator* Project, which is attempting to develop ways to greatly reduce the time needed to mature an effective systems engineer, is being executed as a 5-year project to deliver a strong foundational capability, validate it, and transition it to early adopters. Additional sponsors and funding are being sought to continue growing that capability and to deliver even greater value, consistent with the *SCALE* element of the SERC vision described earlier in Section 1.

In coordination with its sponsors, the SERC has structured its research portfolio into four thematic areas, as shown in Figure 3-1 and described further below:

Figure 3-1. The Four Thematic Areas Being Addressed by SERC Research Tasks and Priorities

- **Enterprises and Systems of Systems:** *Providing ways to develop, characterize and evolve very large-scale systems composed of smaller systems, which may be technical, socio-technical, or even natural systems.* These are complex systems in which the human behavioral aspects are often critical, boundaries are often fuzzy, interdependencies are dynamic, and emergent behavior is the norm. Research must enable prediction, conception, design, integration, verification, evolution, and management of such complex systems.

- **Trusted Systems:** *Providing ways to conceive, develop, deploy and sustain systems that are safe, secure, dependable and survivable.* Research must enable prediction, conception, design, integration, verification, evolution and management of these emergent properties of the system as a whole, recognizing these are not just properties of the individual components and that it is essential that the human element be considered.

- **System Engineering and System Management Transformation:** *Providing ways to acquire complex systems with rapidly changing requirements and technology, which are being deployed into evolving legacy environments.* Decision-making capabilities to manage these systems are critical in order to determine how and when to apply different strategies and approaches, and how enduring architectures may be used to allow an agile response. Research must leverage the capabilities of computation, visualization, and communication so that systems engineering and management can respond quickly and agilely to the characteristics of these new systems and their acquisitions.

- **Human Capital Development:** *Providing ways to ensure that the quality and quantity of systems engineers and technical leaders provide a competitive advantage for the DoD and defense industrial base.* Research must determine the critical knowledge and skills that the DoD and IC workforce require as well as determine the best means to continually impart that knowledge and skills.

These four thematic areas are further divided into eleven programs described below. These programs have the potential to make a transformative impact on DoD and the IC. The SERC Research Council[7], which includes some of the most capable researchers in the field, continues to help shape this portfolio.

- **Enterprises and Systems of Systems**

  - *Enterprise Modeling:* Create, validate, and transition MPTs to model the socio-technical aspects of complex systems of system and enterprise systems, including developing and populating a framework to integrate models created using diverse methods and tools

  - *System of Systems Modeling and Analysis:* Create, validate, and transition MPTs for analyzing and evolving systems of systems and provide support for their technical assessment, including through a "workbench" of analytic tools

- **Trusted Systems**

  - *Systemic Security:* Create, validate, and transition MPTs to ensure systemic security using knowledge of system objectives and operation

  - *Systemic Assurance:* Create, validate, and transition MPTs to provide systemic assurance of safety, reliability, availability, maintainability, evolvability, and adaptability

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[7] See http://www.sercuarc.org/serc-research-council/.

- **Systems Engineering and Systems Management Transformation**

  - *Affordability and Value in Systems:* Create, validate, and transition MPTs to make better decisions on affordability and value in systems

  - *Quantitative Risk:* Create, validate, and transition MPTs to improve risk identification, analysis tracking and management in acquisition and sustainment programs

  - *Interactive Model-Centric Systems Engineering (IMCSE):* Create, validate, and transition MPTs to rapidly model the critical aspects of systems, especially those that facilitate collaborative system development

  - *Agile Systems Engineering:* Create, validate, and transition MPTs that enable rapid, flexible and adaptive SE that can be applied for many kinds of systems in many types of development contexts

- **Human Capital Development**

  - *Evolving Body of Knowledge:* Establish active communities and mechanisms that create and support living bodies of SE knowledge

  - *Experience Acceleration:* Develop an open source community that creates, validates, and transitions technology and content for the use of experiential technology to educate systems engineers and technical leaders

  - *SE and Technical Leadership Education:* Create, validate, and transition curricula and practices to support the instruction and learning of systems and technical leadership for inexperienced students in college and experienced professionals

Between October 1, 2013 and November 30, 2015, research on these eleven programs has been packaged into 30 projects which have been awarded more than $10M in Core funds plus more than $5M from other DoD organizations, including all the Services, Defense Acquisition University, and elements of the Intelligence Community. In several cases, those non-Core funds augmented existing projects; e.g., substantial support for the *Helix* project, begun under Core funding as part of the *Evolving Body of Knowledge* program, has come from the Intelligence Community. In many cases, the SERC launched new research projects as part of existing programs; e.g., the Army funded a project on *Technical Leadership Development* as part of the *SE and Technical Leadership Education* program, and the Marines have funded several efforts to enhance the *Framework for Assessing Cost and Technology (FACT),* which is part of the *Affordability and Value in Systems* program. All of these projects contribute towards achieving the Grand Challenges described earlier in the *Executive Summary.*

4 OBJECTIVES, PRINCIPLES, APPROACH AND TRANSITION PLANNING

4.1 OBJECTIVES

The SERC will have the greatest impact on DoD and the IC by:

1. Conducting long-term research that makes significant progress on the grand challenges

2. Transitioning that research into practice within DoD, the IC, defense industrial base, and other federal agencies; and developing more powerful ways to facilitate such transition

3. Amplifying sponsor resources by forging relationships with other organizations that become partners, contributing their resources and energy to the SERC and adopting SERC research

4. Strengthening the existing SERC culture, mechanisms and focus on collaboration

5. Instituting new approaches to educate future systems engineers and engineers that leverage the full strength and diversity of the collaboration

These approaches align with the SERC's four Operational Principles:

1. Conduct innovative, high-impact research
   a. Focus on research efforts that have the potential of increasing the security and prosperity of the nation
   b. Focus on research which addresses future systems needs
   c. Focus research efforts on systems which can be generalized beyond a given domain and transform the discipline
   d. Only perform tasks which are research oriented (usually publishable when not classified or otherwise restricted)

2. Translate proof-of-principle prototypes to impactful applications
   Work to ensure that there is a path from research results to impact for the security and prosperity of the nation

3. Strengthen and leverage the research network
   a. Ensure that the research is conducted by the best available resources
   b. Bring in new Collaborators and partnering organizations and institutions who provide long-term strategic benefit
   c. Focus on creating a network of academics, industry and government that is sustainable

4. Prepare the next generation
   Provide a focus on education and training research, both in research on education and training, and in the actual education and training of researchers, graduate students, and practitioners

4.2 APPROACH

The general approach to creating the original Technical Plan was first to identify Grand Challenges in each of the four SERC thematic research areas shown in Figure 3-1. These Grand Challenges were formulated

to provide a point of integration between existing programs in each research focus area, and also to provide opportunities to generate new, related research areas. These Grand Challenges also provide inspiration and an integration point for non-SERC universities, federally funded research and development centers (FFRDCs), other University Affiliated Research Centers (UARCs) and industry researchers to perform collaborative research and provide natural transition into use. SERC management worked with the Research Council[8], Principal Investigators and others to craft the Grand Challenges, objectives, and strategy for each of the four research focus areas, and to lay out program descriptions, timelines, anticipated results, and resources required.

Additionally, this Technical Plan continues to assume that:

1. Researchers will be incentivized to find some of their resources from outside Core funds. This could come in the form of matching funds or other forms of resources.

2. Researchers will be incentivized to transition their results into practice. Each project will have a transition plan in place when the project begins with the opportunity for additional downstream funding to facilitate transition to practice and to develop educational materials and courses based on research results that will be shared by all SERC collaborating institutions.

3. Seed funding will be available to explore novel and promising ideas that may be the sources of future breakthroughs. Through an open solicitation process with all of the SERC Collaborators, these ideas will be selected by the sponsors, SERC Research Council and SERC leadership. This past year, the SERC began to solicit, select and provide that seed funding for the first time. An open call to all Collaborators led to more than two-dozen proposals, of which the five most promising were funded as *incubator tasks*. Some may receive additional Core funding beginning in early 2016 or become the basis to solicit sponsorship outside Core funding.

4. Shared IT infrastructure will be available for use by every research project.

4.3 TRANSITION PLANNING

Research in systems engineering is atypical. Traditionally, research discovers new ideas, new properties, or new relationships, leaving it to engineers to take these ideas and make them useful. Systems engineering research usually involves both the early discovery and their packaging for useful application. The value of systems engineering research is in ensuring that other systems engineers can more effectively create value for their stakeholders. No matter what insights SERC researchers achieve through their research, until they are validated by practicing engineers and shown to be useful in effective development and evolution of safe, reliable, and useful systems, they are, per M. Poincare, "useless contraptions." It is for this reason that the SERC includes transition as an increasingly important part of its research methodology and focus.

The SERC approaches transition in a number of ways, beginning when the research effort is defined. Research plans specify a variety of transition actions. The goal is to get "useful combinations" of SE MPTs into the hands of SERC sponsors and stakeholders as quickly and efficiently as possible. MPTs are the SERC's technology. Effective transition into application is key to providing real systems engineering research value.

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[8] See http://www.sercuarc.org/serc-research-council.

As shown in Figure 4-1, many different customer motivations affect their readiness to adopt new technology. The initial target for SERC MPTs is the innovators and early adopters. A SERC MPT successfully transitioned to *innovators* and *early adopters* would be:

- Applied by a small number of practitioners, generally with substantial assistance from the research team
- Demonstrably and credibly delivering its intended value to *early adopters*
- Taught in university programs associated with the research team
- Published in several articles and conferences
- Sustained largely by SERC resources and infrastructure with some support from elsewhere that has the potential to scale up the ability for adoption

However, major impact is realized when the MPTs are transitioned to the early majority. A SERC MPT successfully transitioned to the *early majority* would be:

- Widely applied within its potential market of practitioners
- Demonstrably and credibly delivering its intended value when applied
- Widely taught in relevant university programs
- Articulated in books, videos, papers, social media, and other knowledge channels
- Sustained and improved largely by resources and infrastructure outside the SERC, including having commercial quality tooling, training, and a cadre of experts that aid in its application

Once research has been successfully transitioned to the early majority, market and environmental forces are usually sufficient to complete the transition to the late majority and laggards who are usually convinced by the results achieved by the earlier adopters to satisfy their important needs.
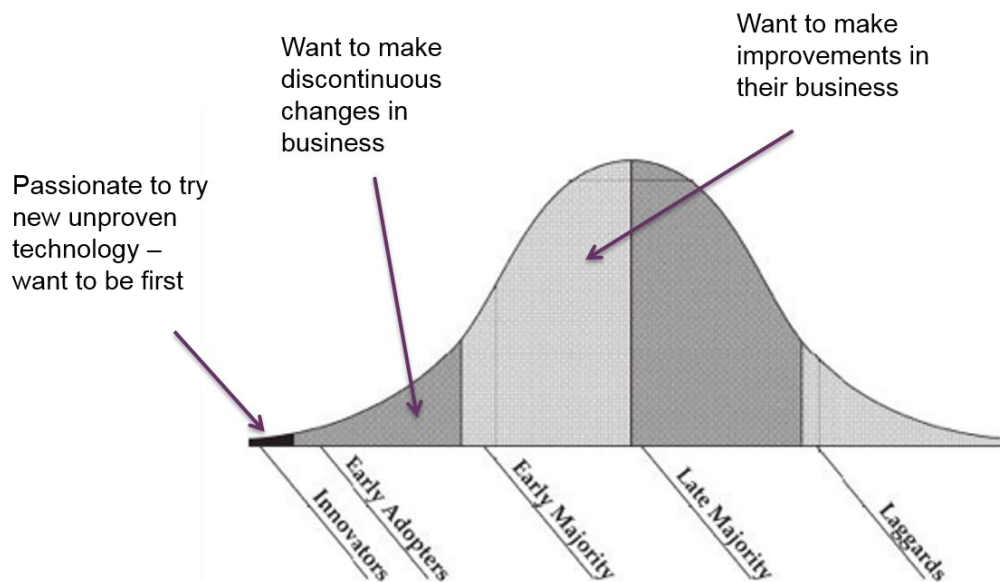

Figure 4-1. Classification of Technology Adopters[9]

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[9] From "Crossing the Chasm", 3rd Edition by Geoffrey Moore, 2014.

As the SERC has continued to grow and mature over the past seven years, the organization has gained significant experience in the area of transition, learning important lessons on what is and is not effective. In addition, the SERC has proactively formed partnerships to strengthen the transition pipeline, building an active network of systems researchers and practitioners. Strong relationships have been forged with several professional organizations, including INCOSE and the National Defense Industrial Association (NDIA) Systems Engineering Division. However, as a research center, the SERC has inherent limitations in the scale at which it can directly support transition. Therefore, the SERC will generally enable and directly support transition only to a small number of *innovators* and *early adopters*. At their discretion, SERC Collaborators may seek to scale MPT transition to a large group of *innovators* or *early adopters* or even seek broader transition of an MPT. Generally, the SERC will play only a very limited or no role in that larger transition. The universities that make up the SERC may take on this role outside of the SERC contract.

Based on past experiences, six principles have emerged that underlie effective transition readiness and progress as shown in Table 4-1. These principles have just recently been documented, but have been applied in varying degrees since the SERC was founded in 2008.

Table 4-1. Six Principles of Successful Transition

Name	Principle
Plan Early	Make successful transition an explicit and well-planned goal from the project's outset
Balance Long and Short Term	Balance the desire for longer-term higher impact research with the importance of shorter-term utility, incrementally delivering results
Pilot Continuously	Continuously engage both practitioner and student pilot groups to improve the utility and confirm the validity of the research
Engage Community	Build strong engagement with outside communities who can become advocates and adopters
Support Centrally	Strengthen SERC-wide infrastructure and incentives to help projects successfully transition their research
Productize	As adoption scale grows, create mature tools, guides, and other artifacts to help adopters succeed, relying where appropriate on outside organizations that will mature research-grade MPTs into production-quality products and services

As noted, each research project needs to establish a transition plan based on the principles described above. Once this has been completed, the transition readiness of the MPTs resulting from the research needs to be characterized. Two dimensions characterize the **readiness** of the MPTs for transition: *relevance* and *practicality*. Relevance is determined by the ability of the new MPT to help Innovators and Early Adopters perform a valuable activity better than they otherwise reasonably could; e.g., does a new approach to understanding the "ilities" of a system architecture really offer relevant insights on reliability, safety, etc. that other MPTs that analyze architectures do not? An MPT has high relevance when it has intrinsically high value and/or differentiating capabilities; e.g., being able to predict with high confidence the cost of building a system of interest or being able to develop an accurate model of the behavior of a system in half the time it would take using other available MPTs.

Practicality is determined by how easily Innovators and Early Adopters can cost-effectively apply it; e.g., is data required for the MPT reasonably available, is automation available to perform the MPT activities, does the MPT work on "real" problems? The bar of acceptability for both relevance and practicality is raised when the MPTs are being transitioned to Early Adopters rather than to Innovators. An MPT has

high practicality when practitioners who are skilled in the activity, but not originally skilled in the MPT, can cost-effectively learn it and consistently and cost-effectively apply it to produce valuable results.

Once transition readiness has been characterized for a project or program, corrective actions or improvements can be made based on the transition principles described earlier. However, it is important to measure the transition **progress** of the MPT to determine the effectiveness of these measures. Two dimensions can characterize how much a SERC MPT has transitioned to Innovators and Early Adopters: *approval* and *adoption*. Approval is determined by how much better adopting practitioners believe the MPT succeeds at delivering value relative to alternative MPTs. It is the driving force for adoption. An MPT has *high approval* when practitioners routinely praise the MPT's impact, cite evidence of that impact, and advocate for its adoption. Adoption is a measure of how widely the MPT is used by practitioners relative to the potential market of the MPT. An MPT has *high adoption* when practitioners from many diverse organizations use the MPT, it is widely taught in universities, and descriptions of it are available from many sources.

Finally, one of the objectives of this Technical Plan is to help the SERC maintain a healthy diverse research portfolio that supports a steady pipeline of transitioning MPTs. As such, each research project will have a transition plan in place based on a stated set of actions supported by the six transition principles. In addition, each research project will have its transition state characterized based on transition readiness (*relevance* and *practicality*) and its transition progress (*approval* and *adoption*) based on project evidence. This information will provide the SERC and its sponsor the ability to determine the appropriate mix of transition characteristics to support their strategic objectives, to take action when necessary and to provide researchers with the tools to improve their transition effectiveness.

5 FOCUS AREAS, PROGRAMS, AND PROJECTS

Since October 2013, every project in the SERC research portfolio has fit into one of eleven programs in the four research areas shown in Figure 3-1. This Technical Plan primarily describes the allocation of Core funds (approximately $5M annually) to 13 existing projects (shown in Table 5-1) and the potential allocation to new, yet unidentified, projects. However, the SERC research portfolio is much larger and more diverse than would be possible with just Core funding. Between October 1, 2013 and November 30, 2015 more than $5M has been awarded to SERC projects funded by the Services, Defense Acquisition University (DAU), the IC, and other organizations in DoD.

Besides directly funding SERC projects, sponsors may provide coordinated funding or in-kind resources that contribute to the execution of SERC projects; e.g., MITRE has coordinated some of its research efforts with tasks in the Systems-Aware Security Project.

Sometimes non-Core funds augment previously existing Core-funded projects e.g., funding contributed by the Intelligence Community towards the Helix Project. At other times, non-Core funds support new projects to which Core funds are later added; e.g., DAU initially funded the Experience Accelerator Project and continues to do so, but Core funds now also contribute. Finally, there have been a number of projects spawned by non-Core investment which have no corresponding Core funding (such as a Navy project exploring how to adopt model-based systems engineering), but which help address one or more Grand Challenges.

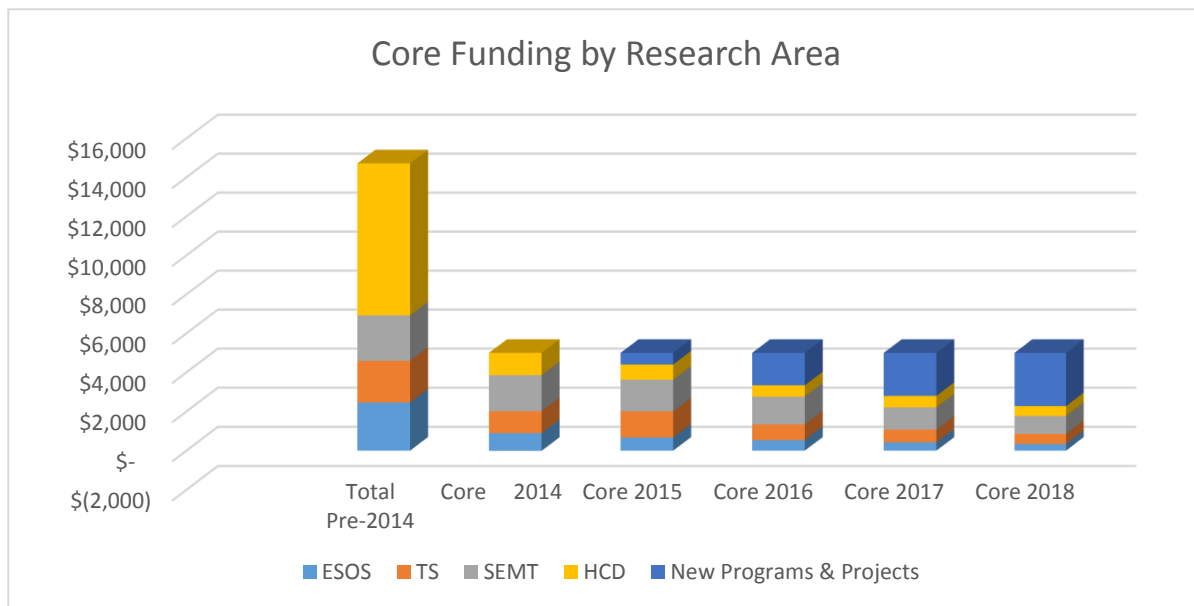Figure 5-1. Core Funding Distribution across Research Focus Areas

Figure 5-1 shows the relative distribution of Core funding between the four research focus areas over the five years of the Plan plus the funding before the Plan started. These funding levels are approximate, intended to serve as the basis for program and project prioritization and sizing decisions. Awarded funds may be expended across fiscal years.

The general philosophy is that each new project receives steady funding for two years, giving that project time to establish its research approach and begin to obtain early results. Funding for that project is then reduced by 20% annually to incentivize the PI to find some funding from non-Core sources. In some cases, projects will end before the five years of this Plan. This has happened to three projects: Flexible and Intelligent Learning Architectures for Systems of Systems (*FILA-SoS)*, *Agile SE Enablers and Quantification*, and *Systems Engineering Expert Knowledge* (*SEEK)*. Moreover, one project, *Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE)*, was in the original Technical Plan, but finished its primary research phase soon after the original Technical Plan was approved. Consequently, *BKCASE* never received Core funding, even though it continues quite successfully to this day in operations and maintenance.

When projects end earlier than planned, freed up Core funds are accumulated in an investment pool that will be used to fund new programs and projects. This reduction incentivizes researchers to seek additional non-Core funding. By the end of 2018, the SERC is targeting three non-Core dollars for each Core-funded dollar.

Additionally, to encourage PIs to transition their research results into university courses, some Core funds may be allocated for PIs to develop educational materials based on their research results. That material will be shared with all SERC Collaborators and perhaps more broadly. The funding level and timing for this allocation is yet to be determined.

Sections 5.1 through 5.4 describe the Core-funded programs and projects in each of the four research areas and provide a short summary of non-Core funded projects in those areas as well. Section 5.5 describes supporting activities that enable the successful execution of these research projects.

5.1 ENTERPRISES AND SYSTEMS OF SYSTEMS (ESOS) RESEARCH AREA

Each DoD/IC Service and Agency, and the larger DoD itself, is an example of an enterprise with all the features of an SoS. Such organizations have the challenge of integrating and evolving multiple portfolios of systems with often-conflicting sets of objectives, constraints, stakeholders, and demands for resources. SoSs generally involve integrating multiple, independently managed systems to achieve a unique capability, therefore involving needs for collaboration and negotiation as well as control. Thus, when viewed as involving both the technical systems and their organizational management, SoSs are enterprise challenges as well. Indeed, both enterprises as systems and as SoSs increasingly face situations in which the classical systems approach of deterministically engineering the system based on relatively static requirements and specified human interactions are insufficient. In such complex systems, human behavioral and social phenomena in collaboration are critical as are cascading impacts from interdependencies; altogether, emergent outcomes are the norm. Research is necessary to determine the foundational SE principles for such systems. These principles can then be used to develop associated SE MPTs applicable to such complex systems.

> **ESOS Area Goal:** Through the use of advanced MPTs, transform the development and delivery of end-to-end defense capability to DoD service-providers and the warfighters for operation in complex organizational and mission environments, so those capabilities have with fewer unintended negative consequences and greater resilience.

5.1.1 ESOS GRAND CHALLENGE AND CURRENT PROGRESS

The ESOS Grand Challenge to achieve the ESOS Area Goal is to:

> Create the foundational SE principles and develop the associated MPTs that enable the DoD and its partners to model (architect, design, analyze), acquire, evolve (operate, maintain, monitor) and verify complex enterprises and systems of systems to generate affordable and overwhelming competitive advantage over its current and future adversaries.

Researchers in the ESOS area have made substantial progress towards meeting the ESOS Research Grand Challenge, particularly in the ability to model and analyze complex interdependencies and the ability to apply models with case studies to guide operations. Examples include the SoS Analytic Workbench, the completed FILA-SoS body of work, valued-based Kanban scheduling for SoS capability development/enhancement, and the use of enterprise systems modeling (a broader notion than simply multi-level models) demonstrated in the context of counterfeit parts. Some adjacent work in linking SoS cost models to architecture evolution via the Systems Modeling Language (SysML) has also advanced, and should be more tightly integrated with other SoS activities for greater impact. Early work in enterprise system models and SysML activity point to the need for even greater effort in visualization and direct tools for decision-support during operations and evolution.

Gaps remain to address the ESOS Grand Challenge, especially in the ability of individual systems to understand implications from the SoS architecture and its behaviors. A greater "situational awareness" for key systems would increase their ability to thrive in the highly dynamic and emergent nature of SoS and Enterprises. Collaborative decision-making tools are promising in this regard. Also, concepts such as quantifying technical debt in existing systems could provide a means for this situational awareness and understanding systems that may support a new or evolved capability.

In addition, although the SoS Analytic Workbench and the counterfeit parts enterprise model have been successfully demonstrated in the SERC Innovation and Demonstration Laboratory (SIDL) (see Section 5.5 for more on this Laboratory), gaps still remain in achieving more ubiquitous and flexible availability to DoD communities. The ESOS Goal requires that the DoD actually use models and tools to make the necessary decisions that lead to superior outcomes. This supports the vision for a form of "SoS Engineering tool repository" that will be hosted in the SIDL. Such a repository would identify the right tools available for a particular problem, where they can be found, and how they can be used in proper context. While this would not prohibit inventors from advancing and distributing the tools in other ways, a repository with administration by SERC could fill a gap until such tools come to market.

5.1.2 STRATEGIES TO ADDRESS THE ESOS GRAND CHALLENGE

Successfully executing the following strategies will make significant progress towards addressing the ESOS Grand Challenge:

1. *Model:* Develop MPTs that allow quick and insightful modeling of enterprises/SoSs so that the effects of changes in policies, practices, components, interfaces, and technologies can be anticipated and understood in advance of their implementation

2. *Acquire:* Develop MPTs that allow insight into enterprise/SoS capability acquisition approaches in the face of significant uncertainty and change to minimize unintended consequences and unforeseen risks

3. *Evolve:* Develop MPTs that facilitate evolving and growing an enterprise/SoS, including insight into different architectural integration and collaboration approaches that facilitate evolution in the face of uncertainty and change in how an enterprise/SoS is employed, the technologies available to realize it, and the environment in which it exists

4. *Verify:* Develop MPTs that allow the properties of an enterprise/SoS to be anticipated, monitored and confirmed during development and evolution, including an enterprise/SoS which includes legacy systems that are in operation while development and evolution are underway

Recall that, for the SERC, *development* of an MPT includes validation and transition.

Directly implementing the strategies are two research programs, described below: *Enterprise Modeling* and *Systems of Systems Modeling and Analysis*.

5.1.3 ENTERPRISE MODELING PROGRAM

This program has been focused on developing a rigorous systems science and engineering foundation for ESOS and on building a community of researchers who collectively will advance ESOS research. In addition, ESOS researchers have been developing domain-specific multi-level or multi-scale models in areas such as counterfeit parts, healthcare delivery, and urban resilience with support from a variety of sponsors.

This foundation and experiences have provided the basis to take on the broader goal of providing enterprise level process mapping, monitoring and control for the ESOS Grand Challenge. As shown in Figure 5.1-1, data, forecasts and reports (including text) flow from the context of an enterprise's ongoing transformation; data and text mining are used to make sense of this flow of information; the insights gained enable computational modeling; the results of which are used to drive interactive visualizations that enable process mapping, monitoring and control.

Pursuit of the ESOS Grand Challenge represents a transition from focusing solely on the design of enterprises and systems of systems to the design <u>and</u> operation of enterprises and systems of systems. In other words, the computational models and interactive visualizations would be run in parallel with actual operations and provide a means for monitoring and the control of operations. In short, the goal is to provide model-based enterprise diagnostics and decision support. Key to this approach is the understanding that mathematical and computational models cannot capture everything that is relevant to the performance of an enterprise. Consequently, designing mechanisms that enable adaptation and hedging is critical. This would enable the operators of complex systems to detect, diagnose, and compensate for deviations of operations from expectations. The complex enterprise systems of interest could range from military operations and acquisition programs, to urban infrastructures and healthcare delivery organizations.
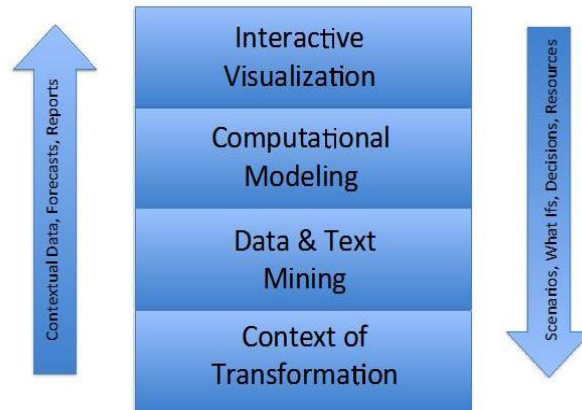
Figure 5.1-1. Enterprise Process Mapping, Monitoring and Control Communication Flows

This research program implements all four ESOS strategies and so far includes one project: *Enterprise Systems Analysis* (formerly known as *Multi-Level Modeling of Socio-Technical Systems*). Table 5.1-1 offers a description of this project and which strategies it supports.

Table 5.1-1. Projects in the *Enterprise Modeling* Program

Project	Started	Purpose	Primary ESOS Supported Strategies
Enterprise Systems Analysis	2012	Develop MPTs to model, understand, and evolve enterprise systems	1, 2, 3, 4

5.1.3.1 Enterprise Systems Analysis Project

Analyzing enterprise systems often requires modeling them on several different levels of abstraction. For instance, DoD spends billions of dollars annually on its modeling and simulation programs[10,11,12]. These models and simulations include million lines of code and model everything from weapon platforms to operational military organizations. Each level, from the performance of individual weapon systems to the success of a campaign, is important, and they all interact. Presumably, the reason one develops better weapons is to improve success on the battlefield and increase national security. Consequently, the seemingly obvious solution to model the DoD enterprise would be to link low-level models computationally to the high-level models. Unfortunately, such models rarely interact with each other without substantial human intervention.

The *Enterprise Systems Analysis* Project originally began as the *Multi-Level Modeling of Socio-Technical Systems* Project with the aim of enhancing capabilities to allow models of different levels of fidelity and

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[10] See http://sim-summit.org/BusinessPractice/pdfs/ROI%20Final%20Report.pdf.

[11] See http://msco.mil/documents/MSJournal2012Fall.pdf.

[12] K. Baldwin and J. Citizen, "Modeling and Simulation Technological and Industrial Base", a briefing on the FY15 NDAA Sec 223, July 30, 2015.

abstraction to interoperate in a dynamic fashion. However, as the work on this effort proceeded, the understanding of the problem has evolved. While multi-level models of enterprises are important, models at different levels of abstraction cannot always be connected computationally. These connections depend critically on the enterprise context and question being asked. As a result, this introduces a number of risks when one attempts to make decisions based on such models. Consequently, enterprises systems analysis has evolved to emphasize using multi-level models to understand the risks inherent to analyzing, designing and, operating enterprise systems and then enabling decision makers to better manage those risks. This will be accomplished by developing methods to enable analysts and decisions makers to:

- Understand when and how enterprise systems can be modeled computationally
- Understand the risks imposed by the aspects of the enterprise that cannot be modeled computationally
- Explore the associated tradeoffs through the use of interactive visualization
- Design mechanisms to adapt to and hedge the risks.

The overall approach is to explore the problem space through a series of case studies that result in the development of enterprise models that analyze problems of interest to DoD. The first case study involves the development of a multi-level model of counterfeit part intrusion into defense supply chains. By using multiple case studies, methods can be developed and evaluated in successive iterations over a broad range of phenomena.

To date, the counterfeit parts case study has involved multiple roundtable sessions that brought together subject matter experts from both government and industry. The resulting model was validated through a series of reviews and is continuing to be refined and enhanced. The intent is to transition the simulation to a government customer by the end of 2016.

Work under this project has led to a new textbook, "Modeling and Visualization of Complex Systems and Enterprises," which was published by John Wiley in July 2015. It includes a ten-step methodology, recommended methods and tools, and a review of a range of modeling paradigms. The book includes many examples and case studies, ranging from counterfeit parts in DoD supply chains to archetypal problems in healthcare delivery, cancer biology, traffic congestion, urban resilience and financial bubbles. The book was used in a course of the same name in the spring 2015 term at Steven's School of Systems and Enterprises with 11 PhD students enrolled, all of whom created demonstrations of interactive enterprise models. These outcomes are evidence of transitions of this project to systems engineering practice.

Table 5.1-2 shows the focus and deliverables in *Enterprise Systems Analysis* through 2018.

Table 5.1-2. *Enterprise Systems Analysis* Project Timeline[*]

Year	Focus	Key Deliverables
Pre – Core	Architectural Assessment of existing commercial practices	Technical reports, summary of interviews and observations
2014 – 2015	Develop modeling methods and strategies	Technical Reports, Counterfeit Parts Simulation
2016 – 2018	Validate modeling methods and strategies	Technical Reports, 2nd Case Study Simulation

The *Enterprise Systems Analysis* Project transition action plan and characterization are shown in Tables 5.1-3 and 5.1-4 below.

Table 5.1-3. Enterprise Systems Analysis Project Transition Actions

#	Transition Action	Principles Implemented
1	Held a series of roundtable sessions with key subject matter experts and stakeholders concerned with the counterfeit parts problem to guide simulation development	• Engage Community • Pilot Continuously
2	Conduct a workshop on the counterfeit parts simulation with key stakeholders from industry and government to demonstrate the value of the enterprise view for policymaking and identify an adopter. Refine the simulation based on feedback and structure for transition.	• Engage Community • Productize
3	Employ a series of incremental DoD application-oriented case studies to explore long-term theoretical implications while spinning off useful increments to practice.	• Plan Early • Balance Long and Short term • Pilot Continuously
4	Present theoretical findings at conferences and publish in peer-reviewed journals to solicit feedback, validate findings, and disseminate work.	• Engage Community

Table 5.1-4. *Enterprise Systems Analysis* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Stevens Institute of Technology now teaches a graduate level class that incorporates findings from this research effort
Progress (approval, adoption)	• The Project has resulted in 4 technical reports, 3 conference papers, 1 published textbook, and 1 submitted journal article • The Project will hold both a SERC peer review of the counterfeit parts simulation and workshop with stakeholders from industry and government

5.1.4 SYSTEMS OF SYSTEMS MODELING AND ANALYSIS PROGRAM

Developing new SoS capabilities while evolving SoSs over time to improve performance and stay current with new technologies remains highly challenging. The complex interdependencies among systems often exhibit managerial and operational independence, yet must work cohesively to achieve an overarching set of capabilities. Tradeoffs between capability and risk are essential decisions that must be addressed for SoS capability planning. Existing tools for such tradeoffs are of limited value when size and/or interdependency complexity is high.

This research program addresses the need to create and mature decision-support tools specifically for evolving SoS architectures and capabilities. The research to date has explored analytical methods to quantify the impact of system interdependencies in the context of SoS capability development as well as broader agent models that address the often-fuzzy influence of stakeholder perspectives in the technical

development activities. Additional research has focused on identifying innovative approaches to support SE in architecting, engineering, and evolving complex SoS. Continuing research in this area will focus on SoS and constituent system situational awareness, strategic approaches for simplifying SoS architectures and their ability to restructure quickly to respond to new needs and missions, as well as the implementation of an SoS Toolbox repository to make maturing SoSE tools generally available to SoS and constituent system development teams.

This research program implements all four ESOS strategies and will address ESOS Strategy 4, *Verify*, with more vigor as pilot studies are completed. It includes one project still underway (*Systems of Systems Analytic Workbench*) and one just successfully completed (*Flexible Intelligent Learning Architectures for Systems of Systems (FILA-SoS)*). *FILA-SoS* produced software that is currently being transitioned via experimentation in the SERC Innovation & Demonstration Lab and also through the annual Complex Adaptive Systems Conference[13].

Table 5.1-5 offers a description of both projects and which strategies they primarily support.

Table 5.1-5. Projects in the *System of Systems Modeling and Analysis* Program

Project	Started	Purpose	Primary ESOS Supported Strategies
Systems of Systems Analytic Workbench	2011	Develop MPTs and an Analytic Workbench construct to house them for the purpose of SoS architecture analysis, redesign and evolution management	1, 2, 3, 4
Flexible Intelligent Learning Architectures for Systems of Systems (FILA-SoS)	2011 (completed successfully Jan. 2015)	Developed proof of concept decision making tool based on the Wave Process Model for architecture selection and evolution; the tool is to be used by an Acknowledged System of Systems Manager	1, 2, 3, 4

5.1.4.1 Systems of Systems Analytic Workbench Project

The objective of this project is to develop an SoS Analytic Workbench (AWB). The AWB is an organized set of computational tools that can aid practitioners in making decisions on evolving SoS architectures and understanding complex interdependencies. Typical questions asked by SoS practitioners have been collected by the project team and mapped to methods/formulations appropriate to produce the desired analytical outputs. A key emphasis in the workbench approach is to relegate the difficult complexities in dealing with highly interconnected systems within an SoS to the methods, while empowering the decision maker with the products expressed in understandable tradespace visualizations. The methods demonstrated so far include: Robust Mean Variance Optimization, Systems Operational Dependency Analysis (extended and enhanced from Functional Dependency Network Analysis developed at MITRE)), Approximate Dynamic Programming, and System Importance Measures (a means for assessing and selecting systems based on resilience properties brought to the SoS). In addition, progress has been made in developing a common input data model from which each method can operate with as little tailoring as possible. To evaluate the progress, a team of analysts from MITRE undertook a series of pilot

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[13] See http://complexsystems.mst.edu/.

demonstrations of the AWB; their report documented useful directions for future enhancements as well as assessment of the value brought by such a capability.

Table 5.1-6 shows the focus and deliverables in the *Systems of Systems Analytic Workbench* Project expected through 2018.

Table 5.1-6. *SoS Analytic Workbench* Project Timeline

Year	Focus	Key Deliverables
Pre – Core**	Evaluate architectures and develop proof of concept simulation	Technical reports and agent based model for selected application domain
2014 – 2015	Develop prototype tools	Technical reports, demonstration of prototype
2016 – 2018	SoS AWB Project (end Fall 2016): Complete pilot studies and integration in the SERC Innovation and Demonstration Lab	Technical reports and articles that document efficacy and use of the AWB MPTs; complete, demonstration of prototype application

**Note: Funding shown from Pre-Core through 2014-15 included both SoS Analytic Workbench and FILA-SoS projects

In addition to the SoS Analytic Workbench itself, several other tools and techniques have been developed or identified to support SoS architecture assessment, architecture evolution, and capability engineering and development – some as a result of other SERC research areas. To date, information about these tools and techniques primarily resides in SERC and other technical reports. In 2016, efforts will begin to catalog these tools and techniques in a repository and include copies of any tools that have been developed as part of SERC research or other non-Core SoS funding that can be made generally available to the SERC and engineering communities. Once these tools have been identified and cataloged, further analysis can be conducted with respect to coverage of System of Systems Engineering (SoSE) activities/tasks, gaps with respect to difficult or complex SoSE activities, and interoperability of tools, along with guidance on how tools can be used to either inform or address SoS problems, issues, and concerns.

The *SoS Analytic Workbench* Project transition action plan and characterization are shown in Tables 5.1-7 and 5.1-8 below.

Table 5.1-7. *SoS Analytic Workbench* Project Transition Actions

#	Transition Action	Principles Implemented
1	The SoS Analytic Workbench has been studied, exercised, and evaluated in a pre-pilot phase by MITRE Corporation. Pre-pilot activities have been conducted with Army Research Lab analysts for application to live, virtual, constructive test design.	• Pilot Continuously • Engage Community • Productize
2	Demonstrations and discussions ongoing with Johns Hopkins Applied Physics Lab (JHUAPL) and the US Air Force. To support these activities, graphic user interfaces and input test cases have been developed and refined.	• Pilot Continuously • Engage Community • Productize
3	A CRADA between Purdue University and Navy NSWC Dahlgren has been signed and is being applied in which Navy experts will conduct exploratory pilot applications of the SoS AWB as it relates to enhancement of Navy Interoperability & Integration studies.	• Plan Early • Pilot Continuously

Table 5.1-8. SoS Analytic Workbench Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Purdue University teaches a graduate level class (AAE560 Systems of Systems Modeling and Analysis) that has been significantly enhanced by the findings from this research effort
Progress (approval, adoption)	• Several journal and conference papers have been generated, including a recent publication in CSER 2015 and a paper in the INCOSE Systems Engineering Journal

5.1.4.2 Flexible Intelligent Learning Architectures for Systems of Systems (FILA-SoS) Project

The *FILA-SoS* Project developed an integrated model based on the Wave Process Model which serves as a decision making aid for an SoS manager. The *FILA-So*S model does so by using a straightforward system definitions methodology and an efficient analysis framework that support rapid exploration and understanding of key trade-offs and requirements for a wide range of SoS stakeholders and decision makers. The *FILA-SoS* model addresses four of the most challenging aspects of SoS architecting:

1. Dealing with the uncertainty and variability of the capabilities and availability of potential component systems

2. Providing for the evolution of the SoS needs, resources and environment over time

3. Accounting for the differing approaches and motivations of the autonomous component system managers

4. Optimizing SoS characteristics in an uncertain and dynamic environment with fixed budget and resources

Three notional SoSs have been modeled: Conceptual Problem for aircraft carrier performance assessment, for intelligence surveillance and reconnaissance, and for search and rescue.

As shown in Figure 5.1-2, the FILA-SoS framework offers several unique capabilities that aid the SoS manager for a variety of complex systems such as logistics and cyber-physical systems. These capabilities include:

• Being an integrated approach to model and simulate SoS systems that incorporate evolution for multiple waves,

• Having a modular structure that enables models to be run independently or in conjunction with each other,

• Offering models for both architecture generation and SoS behavior as well as models to negotiate system behavior between SoS and individual systems,

• Helping understand emergent behavior of systems in the acquisition environment and their impact on SoS architecture quality,

• Serving as a means to study the dynamic behavior of different types of systems – non-cooperative, semi-cooperative, and cooperative,

- Enabling identification of intra- and inter-dependencies among SoS elements and the acquisition environment,

- Providing a "what-if" analysis relying on variables such as SoS funding and capability priority; those variables can be changed as the acquisition progresses through wave cycles,

- Simulating any architecture through colored petri nets,

- Simulating rules of engagement and behavior settings where there is a mix of whether systems are non-cooperative, semi-cooperative, or cooperative, and

- Acting as a test-bed for decision makers to evaluate operational guidelines and principles for managing various acquisition environment scenarios.

Future capabilities include extending the modeling capability to accommodate multiple interface alternatives among systems and incorporating risk models into environmental scenarios.
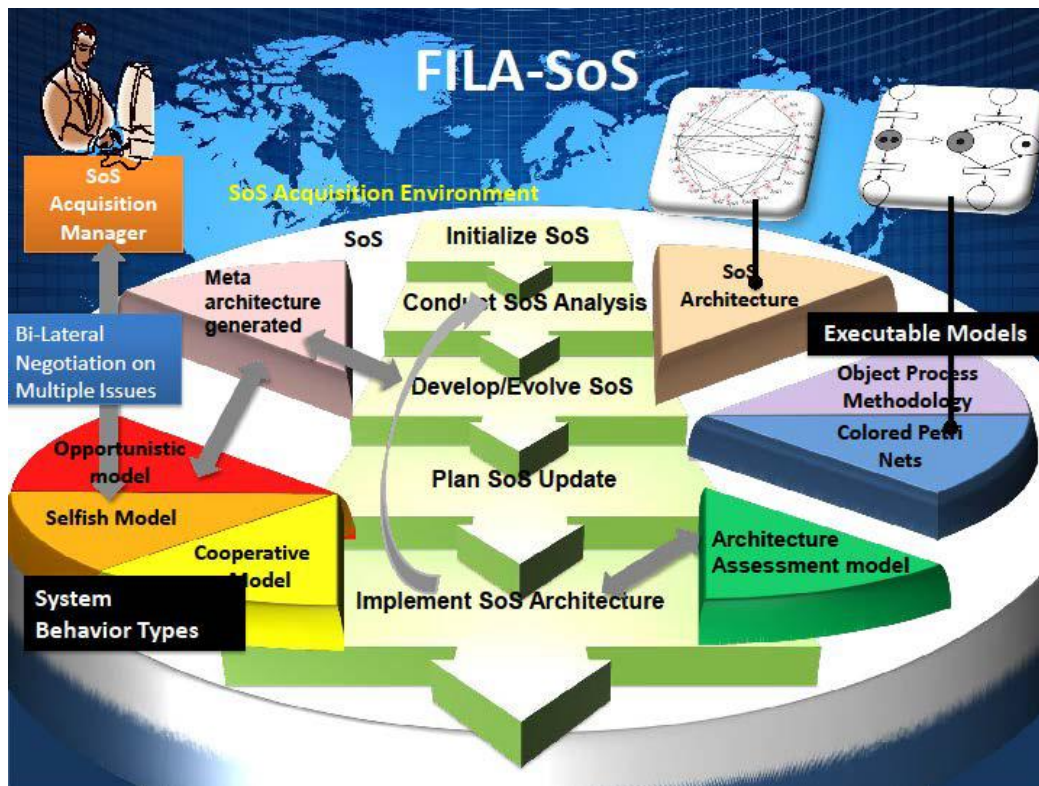

Figure 5.1-2. FILA-SoS Capabilities

Table 5.1-9 shows the focus and deliverables in the *FILA-SoS* Project through its completion.

Table 5.1-9. *FILA-SoS* Project Timeline[*]

Year	Focus	Key Deliverables
Pre – Core	Develop the basic structure of the FILA-SoS model based on the Wave Process Model and develop mathematical models for each independent component	Technical reports, journal and conference publications. Prototype software to demonstrate the workings of the FILA-SoS model on two notional SoSs: (1) Surveillance, Intelligence and Reconnaissance, and (2) Search and Rescue
2014	Development of algorithms that may be integrated into FILA-SoS to answer research questions on subsystem behavior and on how to incentivize systems to participate in an SoS	17 volumes of technical reports, journal and conference publications, FILA-SoS Version 1.0 Scalability Validation with MITRE Data, and demonstration of the integrated model though a conceptual problem of assessing the performance of an aircraft carrier

The *FILA-SoS* Project transition action plan and characterization are shown in Tables 5.1-10 and 5.1-11 below.

Table 5.1-10. *FILA-SoS* Project Transition Actions

#	Transition Action	Principles Implemented
1	The FILA-SoS model was presented to "SoS Concept Development and Assessment, SoSITE" at Boeing Company and the approached was transferred to Boeing Engineering by a Missouri S&T Systems Engineering PhD student.	• Productize • Engage Community
2	The FILA-SoS model is being integrated to other research projects in the ESOS research area in the SERC Innovation and Demonstration Laboratory using the conceptual problem for assessing the performance of the aircraft carrier. It is also possible to use this new facility to demonstrate the FILA-SoS model to interested parties for its implementation to a specific SoS or cyber-physical system.	• Engage Community • Productize
3	Fall 2015 Missouri University of Science and Technology SySEng 6239 was completely restructured to accommodate algorithms and integrated model structure developed in FILA-SoS research. The first version of FILA-SoS prototype software was the basis of small project tasks to be conducted during the course. The intent is to make these course materials available at the Naval Postgraduate School and the Air Force Institute of Technology to be used in conjunction with the SERC Innovation and Demonstration Lab during Spring or Fall 2016 in similar courses that they teach.	• Plan Early • Engage Community • Productize
4	Successfully completed FILA-SoS project has spurred the development and growth of the Complex Adaptive Systems Conference, along with the CSER, a significant community building and sharing forum to transition ideas and tools	• Engage Community • Balance Long & Short Term

#	Transition Action	Principles Implemented
5	The second version of FILA-SoS prototype software (beyond the scope of this project) will incorporate models developed to answer stated research questions. This requires professional software development, as research software prototype is not sufficient for this purpose. It may be possible to work with software companies or John Hopkins Applied Physics Lab for possible transfer of the research to be developed further for industrial use.	• Productize

Table 5.1-11. *FILA-SoS* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Missouri University of Science and Technology teaches graduate classes (SySEng 6104 Systems Architecting and SySEng 6239 Smart Engineering System Designs) that have been significantly enhanced by the findings from this research effort.
Progress (approval, adoption)	• Nineteen journal and conference papers have been generated based on this research project and the annual Complex Adaptive Systems Conference was and will continue to be a good outlet for diffusion of this research.

5.1.5 ESOS AREA NON-CORE FUNDED PROJECTS

During the time of the Technical Plan, the SERC has been awarded one ESOS non-Core funded project. The project, which is briefly described in Table 5.1-12, is still active as of the time of the publication of this Plan.

Table 5.1-12. ESOS Area Non-Core Funded Project

Project	Sponsor	Description
Army Lethality Study	OSD	Perform a systems-oriented study to assess the current state of the Army's lethality capability and provide actionable recommendations to make the changes needed to transform that capability at an enterprise level.

5.2 TRUSTED SYSTEMS (TS)

The organization of its assets into net-centric systems of systems (NCSOS) has enabled DoD to much more rapidly and effectively see-first, understand-first, act-first, and finish decisively in its operations. However, this implies that each of its assets needs to achieve higher levels of trust as part of the NCSOS, as compared to its previous role as a standalone platform, all the while retaining or improving its previous speed and effectiveness. Achieving those levels of trust is extremely challenging.

The SERC Trusted Systems (TS) research area addresses this challenge, in part, by balancing traditional reactive cyber-security defenses with pro-active mechanisms, making attacks more difficult and more expensive. It combines this approach with increased and continuous application of advanced assurance capabilities that concurrently address not only security but also safety, reliability, availability, maintainability, usability, interoperability, and resilience.

TS Area Goal: Transform system assurance from a late, reactive activity into an early and continuous, pro-active orchestration of advanced assurance MPTs, in ways that balance the simultaneous achievement of cyber-security trust and assurance with complementary MPTs for assuring safe, reliable, available, usable, interoperable, and resilient mission cost-effectiveness.

5.2.1 TS GRAND CHALLENGE AND CURRENT PROGRESS

The TS Grand Challenge to achieve the TS Area Goal is to:

> Achieve much higher levels of system trust by applying the systems approach to achieving system assurance and trust for the increasingly complex, dynamic, cyber-physical-human net-centric systems and systems of systems of the future.

With respect to security, this activity's mainline concept of adding a layer of security through securely monitoring systems for system illogical behaviors that can be assessed as most likely caused by a cyberattack has received significant recognition, both within and outside of the DoD. The approach uses a highly secured Sentinel as both a valuable addition to security and as an economically advantageous system architecture, compared to directly securing the monitored system to a similar level of security in the Sentinel. In particular, application to physical systems has been seen as an important opportunity for application of this technological approach, as the development and securing of a Sentinel can include elements such as independent sensors and bounded operator control rules as the basis for effective and economical design approaches for detecting attacks. This has resulted in the start of prototyping projects for a DoD radar, a 3D printer (NIST), police cars (Virginia State Police), and an Army/Air Force image exploitation system using a private cloud-based Sentinel.

In the process of conducting this research, two important gaps in the needs for security have been recognized. First, in military operations, individual systems are clustered into SoSs that conduct missions. The missions are the capabilities that need added security, while the individual systems are the specific locations for providing the elements of security. We have seen that in an SoS: (1) attacks can be developed to exploit the seams between individual systems; (2) attacks occurring in a particular system can result in symptoms that appear in another; and (3) defense alternatives of certain mission functions that can be addressed in more than one system, can sometimes be much more easily and economically accomplished in one system as compared to another system. This leads to the recognition of the need for better understanding, analysis and design for mission-level security. In 2014-2015 the SERC developed an SoS test bed including multiple ground-target sensor types (video, infrared, acoustic), a radar for airborne targets, an unmanned aerial vehicle, an image exploitation system and a ground defense command and control system. The Secure Mission Laboratory enables the start of a research effort that expands the Sentinel concept to the mission level, including multiple Sentinels providing the basis for managing cyberattacks from a mission perspective. A partnership, initiated through the Naval Cyber Command, with JHUAPL has started working on new concepts for mission level security, with the objective of engaging operational military leaders into the process of mission security requirements, and engaging the technology community into new approaches that more directly relate solutions to mission performance.

Second, the emergence of new DoD initiatives related to highly automated/autonomous systems drives a need for more advanced risk containment technologies. These technologies include both cybersecurity and other technologies that offer resilience that assures continuous system operation. The Sentinel

approach has clear overlaps with other risk containment approaches (e.g., fault tolerant design, software assurance solutions), providing an opportunity to integrate these opportunities from (1) a design concept viewpoint, (2) an implementation viewpoint, and (3) in certain cases, from an integrated implementation viewpoint. In addition to technology design issues, other issues related to the role of people in these systems contain significant overlaps as well. This year, the cybersecurity project has included a human factors element, addressing human confidence in responsive decision-making in the event of a cyberattack. The experimental questions being addressed in the human factors project have been seen to overlap with questions faced by the Air Force autonomous systems community at the Air Force Research Laboratory. The Air Force Institute of Technology is engaged with the University of Virginia in addressing the cybersecurity project and is actively evaluating the synergistic opportunities for future research. The SERC anticipates identifying important overlapping interests and defining new project objectives for 2016 that address the synergistic opportunities.

In the area of assurance, this goal can only be met through a comprehensive and aggressive SE approach that encompasses three critical dimensions of consideration: (1) the structure of systems, including architecture and accounting for various kinds of dynamism for the purpose of resiliency and autonomy, (2) the process and engineering activities by which systems are constructed, evolved, and sustained, including mechanisms for measurement of critical attributes and for management of alternatives and commitments, (3) the supporting models and techniques through which evidence can be created to support assurance judgments. The SERC's focus is on the last of these three – achieving high levels of trustworthiness – but it is recognized that a strategic approach is required that builds on the interplay of these three critical dimensions of consideration. This interplay, evident in the diagnosis of assurance failures and root cause analyses, defines the scope of this grand challenge.

The strategy taken in this area has four principal features: (1) the expression, retention, and analysis of diverse kinds of information related to requirements, design, implementation, and operation; (2) mechanisms whereby the potential consequences of decisions and engineering commitments can be understood as early as possible in the process, including approaches such as iteration, prototyping, modeling and simulation, analytic methods, and other approaches; (3) support for these practices (information management and tight feedback) across the entire lifecycle starting from the earlier stages of requirements formulation and encompassing architecture, design, implementation, evaluation, integration into operating environments and ecosystems, and operation; and (4) ability to respond effectively to changes in the mission operating environment, the SoS context, and the infrastructure environment.

These four features give rise to the seven areas of technical emphasis identified in the Systemic Assurance Program. Initial emphasis to address the TS Research Grand Challenge is on establishing a baseline for assurance standards and practice, with emphasis on developing a framework for the evaluation of practices and techniques. This framework consists of a set of meta-criteria – criteria through which evaluation practices (including practice-specific criteria for process and structure) can themselves be assessed and compared. Importantly, the meta-criteria also enable assessment of the potential impact of emerging practices, models, tools, and techniques. A candidate inventory of meta-criteria has been identified and in future work will be refined with the development of scales and value weightings. Additionally, considerable technical progress has been made on techniques for design, modeling, and analysis, focusing at three crucial stages of SE: requirements, architecture and design, and implementation.

This initial effort will enable progress on aspects of technology and practice that relate to the representation and management of diverse kinds of evidence, including implementation artifacts, models and analysis results, and dependency and traceability linkages among these things. This creates the foundation for an explicitly evidence-based approach that offers a pathway for incremental improvement of capability along with a framework of meta-criteria for evaluation of progress.

5.2.2 STRATEGIES TO ADDRESS THE TRUSTED SYSTEM GRAND CHALLENGE

Successfully executing the following strategies will make significant progress towards addressing the TS Grand Challenge:

1. *Design for System Assurance and Trust:* Develop design patterns and systems architectures, with corresponding systems engineering principles guiding application, and associated design analysis MPTs for early assurance of needed properties

2. *Understand the Cost of Assurance and Ensure Cost-Effective Assurance:* Develop MPTs that enable understanding, predicting, and ensuring the cost-effectiveness of implementing high-assurance policies and requirements, especially on complex systems and complex systems of systems

3. *Understand and Ensure Balanced Tradeoffs Between Assurance "ilities" and Other "Ilities":* Develop MPTs that enable understanding, predicting, and ensuring cost-effective relationships among assurance policies/requirements and other "ilities", such as usability, interoperability, and maintainability

4. *Measure System Assurance:* Develop MPTs that allow measuring "how much" assurance of needed properties a system has, and that permit comparison of the relative assurance and trust provided by alternative systems

Recall that, for the SERC, *development* of an MPT includes validation and transition.

Two research programs directly implement these four strategies:

- *Systemic Security.* The most compelling need for assurance of trust is in the area of system security. Given the numerous sources of security breaches available at low cost to attackers, a major concern is to make DoD systems, SoSs, and enterprises harder to attack, while simultaneously making them more difficult and expensive to penetrate and damage.

- *Systemic Assurance.* Besides security attacks, there are numerous sources of system disruption such as natural disasters, system misuse, system overload, system component wear out, and defects in a system's requirements, design, or construction. Preventing or otherwise addressing these disruptions, which cause loss of stakeholders' lives, health, capability, property, or financial assets, require significant improvements in trust not only for current systems, but for the more complex and dynamic DoD systems, SoSs, and enterprises of the future.

In addition, improvements in system trust have been and are being addressed in the other SERC research areas, particularly in SEMT and its current projects: *System Qualities, Interactive Model-Centric SE*, and *Quantitative Technical Risk*. Example contributions from these and earlier SEMT projects include SERC insights such as those from projects addressing technical, integration and manufacturing maturity level

assessment, risk management precepts, the enterprise management approach to quantifying early-SE risks, the MIT epoch-era approach to assurance under uncertainty, and the set-based vs. point-design approach to assurance of systems undergoing continuing and extensive change. The synergies among these research projects will be addressed and enhanced by periodic cross-research-area workshops.

5.2.3 SYSTEMIC SECURITY PROGRAM

The goal of the *Systemic Security* Program is to develop MPTs that enable safe, secure, dependable defense systems that are resilient to cyber and other threats through systemic security approaches that complement current, incomplete perimeter/network. This goal is being achieved by reversing cyber security asymmetry from favoring our adversaries (small investment in straightforward cyber exploits upsetting major system capabilities), to favoring the US (small investments for protecting the most critical system functions using systems-aware cyber security solutions that require very complex and high cost exploits to defeat). Building on the four TS Area strategies to address the TS Grand Challenge, the *Systemic Security* strategies are:

1. *Design for System Security*. Develop MPTs that develop solution selections on a mission security basis as opposed to a subsystem basis, recognizing that the interaction between subsystems provides opportunities for adversaries regarding cyberattacks, and also provides potential economies for defenders regarding identification of the most cost effective way for achieving mission security.

2. *Develop design patterns and security architectures that enable security to be based on the specific properties of the system and its implementation as a complement to traditional perimeter strategies:* Address security of weapon systems, sensor systems, physical plant systems as well as IT systems within the context of SoSs applied to military missions; e.g., air defense, point target defense, and warning systems. Account for operational procedures and human factors in the SoS context.

3. *Support security requirements assessments that directly address cost and achievement of cost-effective security:* Develop MPTs that enable understanding, predicting, and ensuring the cost-effectiveness of implementing specific security policies and requirements, especially on complex systems and complex systems of systems

4. *Explore overlaps and difference in security monitoring:* Initiate exploration efforts that identify the overlaps and differences between security monitoring as employed in the Systems-Aware concept and performance monitoring for autonomy, recognizing that autonomous systems will need to include monitoring functions for performance assurance.

This research program implements all four TS strategies above. Table 5.2-1 offers a description of the single long-term project currently underway in this program and which strategies that project primarily supports.

Table 5.2-1. Projects in the Systemic Security Program

Project	Started	Purpose	Primary TS Supported Strategies
Systems-Aware Security	2011	Develop and then refine Systems-Aware MPTs and pilot them in multiple application areas	1, 2, 3, 4

5.2.3.1 Systems-Aware Security Project

In 2011, SERC RT-28: *Systems-Aware Security* developed a rapid prototype security capability that includes (1) data continuity checking within the application, (2) real-time virtual configuration hopping of selected command and control functions across multiple operating systems to provide defense through diversity, (3) real-time physical configuration hopping to both provide defense through diversity and resilience in the face of successful attacks, and (4) a closed loop control system for automatic restoration from a successful attack. In 2012-2013, SERC RT-42: *Security Engineering Pilot* developed a prototype flight-capable security capability directed toward an unmanned air vehicle (Outlaw aircraft containing an embedded Piccolo flight control system) carrying a pre-existing set of surveillance equipment (video/infrared cameras, radar, and a signals intelligence package).

The original focus of the project has concluded. It served to provide a greater understanding and visibility for the Systems-Aware concept and it identified the need and opportunity for addressing mission-based security and human factors from an SoS perspective. Subsequent activities will involve the tailoring of the capabilities to other domains, and associated evaluation and refinement, along with monitoring and refinement of existing fielded capabilities.

Table 5.2-2 shows the focus and deliverables in the project through 2016. Continuing extensions and upgrades will be pursued in 2017 and 2018.

Table 5.2-2. *Systems-Aware Security* Project Timeline[*]

Year	Focus	Key Deliverables
Pre – Core	Concept definition, prototyping, piloting	Initial Systems-Aware Security capability
2014	Extended evaluation, refinement, and Packaging	Tailorable Systems-Aware Security capability
2015	Mission level security concept development	SoS Systems-Aware Security capability concept and prototype, tool-supported methodology for development security requirements, exploration of human factors, rapid security prototype for an existing military system (AIMES)
2016	Through concept refinement efforts and prototyping efforts, direct application of 2015 results toward application into existing military systems	Two new domain Systems-Aware Security capabilities

The *Systems-Aware Security* Project transition action plan and characterization are shown in Tables 5.2-3 and 5.2-4 below.

Table 5.2-3. *Systems-Aware Security* Project Transition Actions

#	Transition Action	Principles Implemented
1	Initiated collaboration with Navy 10th Fleet (Cyber Command) and JHUAPL in addressing requirements methodology and support tools, including organizing a workshop to introduce the research to them. Met with large Aegis Program Manager group to engage their interest.	• Plan Early • Engage Community
2	The University of Virginia has licensed Systems-Aware technology to a start-up company (MSI) engaging in offering new security products and services related to Systems-Aware concept and have initiated efforts to gain new patents.	• Engage Community • Pilot Continuously • Productize
3	Integrated AIMES prototype into a live prototype SoS environment to highlight mission-oriented approach to security including an operational system.	• Engage Community • Pilot Continuously • Productize
4	Initiated projects with NIST on 3D Printers and Virginia State Police focused on automobiles that have both provided confirmation of potential value and provided new elements of learning for transition into military systems.	• Engage Community • Pilot Continuously • Productize
5	Include Air Force Institute of Technology as part of the Human Factors research efforts.	• Engage Community
6	Involve the DoD Chief Information Officer in the definition of the Cloud computing portion of the project.	• Plan Early • Engage Community
7	Involve the Deputy Assistant Secretary of Defense for Emerging Capability and Prototyping) in supporting the definition of a rapid prototyping project that is directed toward development of an operational prototype radar system with System Aware security capabilities.	• Plan Early • Engage Community

Table 5.2-4. *Systems-Aware Security* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Application to existing Army/Air Force AIMES system, etc.
Progress (approval, adoption)	• The project has published 5 journal articles with one currently under review, 4 conference papers, 4 technical reports, and numerous public presentations. • Air Force, Navy, DoD Chief Information Officer are engaged in project efforts; MITRE, JHUAPL have provided support to the project • Through the Virginia Cybersecurity Commission, have initiated an economic development plan that addresses support for education and research activities that bring together the cyber-physical systems community with the cybersecurity community

5.2.4 SYSTEMIC ASSURANCE PROGRAM

Besides security, the engineering of resilient DoD systems requires assurance of safety, reliability, availability, durability, survivability, maintainability, evolvability, adaptability, and sustainability. Systems cannot be deployed until customer organizations judge them fit for use in the mission environment. These assurance judgments must be based on evidence that a system manifests not just the necessary functionality but also these quality attributes, and at a level appropriate to the operating environment. All of this assurance needs to be achieved for increasingly complex, dynamic, cyber-physical-human net-centric systems, SoSs and enterprises with needs for rapid response incompatible with most heavyweight assurance MPTs. Carnegie Mellon University (CMU) has been a leader in developing assurance MPTs in such areas as architectural style analysis, race and deadlock detection for multicore and other concurrent systems, appropriate test case generation, model checking, and assurance-case analysis. These techniques must be applied not just in anomaly detection, but also leading to stronger possibilities for positive assurance and to greater scalability to large systems and to more rapid execution. These techniques have been successfully applied in such areas as the High Level Architecture analysis for networked DoD models and simulations, cyber-physical robotic systems, and extremely large commercial Java programs.

The *Systemic Assurance* Program currently has one project, of the same name, that builds on these capabilities and data sources to improve both the level of assurance obtainable and the cost-effectiveness of assurance-related effort, with a goal of rapid recertification to support evolving components and systems.

Table 5.2-5 below offers a description of the sole project currently in this program.

Table 5.2-5. Projects in the *Systemic Assurance* Program

Project	Started	Purpose	Primary TS Supported Strategies
Systemic Assurance	2013	Develop MPTs that combine technical analysis of system artifacts and requirements and architecture techniques to promote assurance and resiliency	1, 2, 3, 4

5.2.4.1 Systemic Assurance Project

The Systemic Assurance Project combines technical analysis of system artifacts and requirements and architecture techniques to promote assurance and resiliency. An important goal is to develop incrementally composable combinations of MPTs and data based composition guidance for obtaining the most cost and schedule-effective combinations for the assurance of necessary system properties. Particular areas of emphasis will be exploiting analogies with successful techniques in other domains, such as building codes; better management of chains of evidence to support ongoing re-evaluation for rapidly evolving systems both in development and in sustainment/modernization; enhancing MPTs with language extensions for assurance assertions or context metadata; support for dynamic adaptiveness and resiliency in architectural design; and data management and metrics for more evidence-based design, development, and decision support.

Reflecting strong natural ties between the *Systemic Assurance* Project and the ilities Tradespace and Affordability Systems Qualities Project (SQ) described in 5.3.3.1, extensive coordination will be pursued between the two projects.

The *Systemic Assurance* Project implements all four TS Area strategies above. It includes seven research and technology subprojects led by senior CMU researchers, with extensive internal coordination mechanisms to exploit the synergies among the various technical approaches. The CMU team members have an extensive network of collaborations and partnerships with DoD activities, other government agencies, the Software Engineering Institute, other SERC universities, and numerous industrial firms.

The *Systemic Assurance* Project has four technical themes related to advancing assurance capability:

- *Evidence and traceabilit*y*.* Facilitate early validation by accumulating assurance-related evidence and creating traceability structures during development.

- *Requirements, architecture, composition, variabilities*. Address assurance goals in the earliest phases of development. Enable composition of assurance judgments for components into overall judgments for systems.

- *Direct analysis.* Use semantics-based techniques to enhance confidence and scalability, focusing on challenges significant for modern systems, such as: framework protocol compliance, highly versioned systems, automatic defect repair, safe concurrency, and other areas.

- *Combined methods*. Integrate multiple methods to evaluate quality attribute requirements for heterogeneous systems, combining informal and formal, static and dynamic, and development and operational monitoring.

The research team addresses these themes through seven subprojects:

1. **Practice baselining.** Develop baseline and intervention models for a selection of current standards and practices (identified in collaboration with DoD stakeholders), refining technical understanding of gaps and limitations. This baselining effort is essential to support a measurement-based approach to documenting the impact of the proposed new technologies and process interventions. This includes identifying the key criteria and dimensions of measurement.

2. **Evidence building.** Undertake engineering design effort focused on integrating improved capability for traceability and other features required to support explicit modeling and management of chains of evidence. A key focus is to demonstrate that it is possible to enhance existing tools and environments, including both integrated development environments and team tools, with relatively little disruption to established team practices and metrics.

3. **Recertification practice.** Design and implement experiments to address the challenge of rapid recertification. These include capturing evidence and assurance-related reasoning (assurance cases, models, analyses, configuration management, etc.). This area of rapid recertification is critical to iterative, incremental, and staged development practices. It is also critical to systems with supply chains that include externally developed components and infrastructure such as commercial and open-sourced databases, operating systems, frameworks, and libraries. (Almost all larger-scale software-reliant systems have this characteristic.)

4. **Architecture assessment.** Develop a framework for assessment of architecture-derived quality attributes, focusing on architectural modeling and the relationship of architectural and

compositional models with quality outcomes. This is essential in order to ensure that key decisions made at early lifecycle phases will have intended quality outcomes.

5. **Requirements and quality validation.** Develop requirements elicitation and management approaches that better address quality and policy objectives. Requirements elicitation and management is one of the earliest areas of focus in an engineering process, and decisions at this point can have tremendous leverage on quality outcomes. This work is directed at providing more immediate assessments of the potential outcomes of early requirements-related decisions. By improving models, it becomes possible to better manage the linkage of requirements and architectural decisions.

6. **Technical quality attributes.** Augment and collaborate with diverse existing efforts focused on technical means to address particular quality criteria. Many of these quality criteria are emerging as significant challenges because they tend to defy conventional testing and inspection techniques. These include, for example, a number of attributes related to safe concurrency, compliance with application program interface rules-of-the-road, cyber-physical architectural compliance, state and access management for shared objects, taint and flow and other security-related attributes, and others.

7. **Tools, automation, and usability.** Identify and advance areas in support of increasing automation, in order to reduce workload of developers and evaluators and to advance existing workload forward in the process, with immediate rewards. The purpose of this is to frame an ultimately more quantitative business case for adoption based on increased return on investment for assurance-related effort and reduced uncertainty (lesser variance in estimate "cones"). This is supportive of the longer-term goal of a "positive benefit" model for the adoption of assurance-related practices. It also supports a stakeholder-engaged process model analogous to building codes.
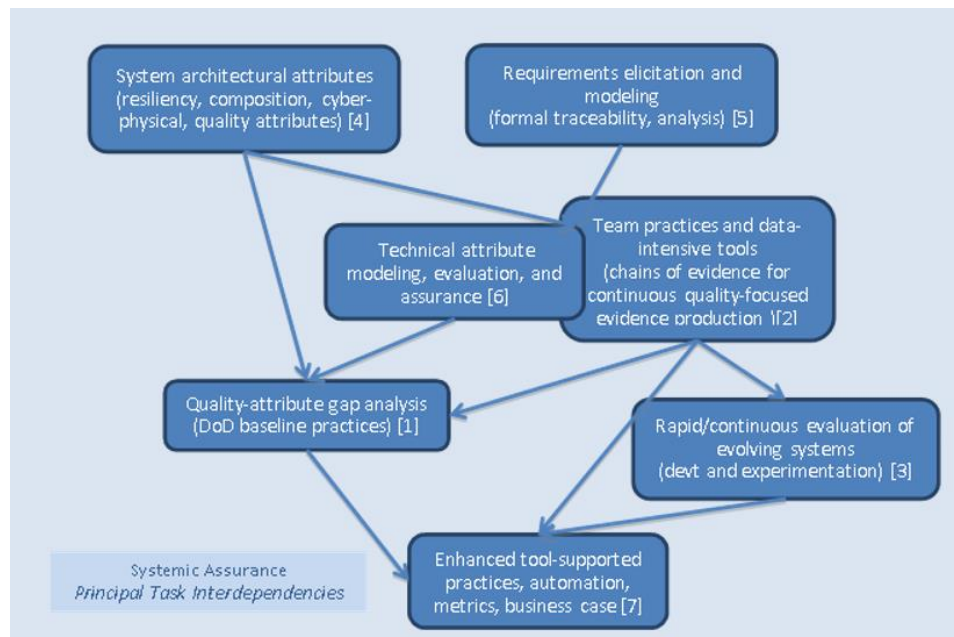

Figure 5.2-1. Systemic Assurance Principal Task Interdependencies

There are important synergies and interactions among these seven subprojects, with the principal features outlined in Figure 5.2-1 above (subproject numbers are in brackets).

Table 5.2-6 shows the focus and deliverables in the *Systemic Assurance* Project.

Table 5.2-6. *Systemic Assurance* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Startup	Prepare for and hold kickoff meeting with sponsor, Systemic Security, and System Qualities representatives
2014	Initiate efforts in subprojects 1, 4, 5, and 6.	Identify principal candidate software code bases and cyber-physical systems for empirical studies. Candidates include commercial and government partner systems and significant open source systems of government interest. Begin empirical studies and solution explorations.
2015	Continue effort on subprojects 1, 4, 5, and 6. Identify most promising solution options, begin solution research and development. Initiate effort on subprojects 2 and 7.	Complete initial baseline analysis and identify feature points to address in framing potential revised practices. Identify technical blockers and potential remediations.

Initiate work on tool design, building on capabilities of established integrated development environment and team tools. Develop a "minimal perturbation" model that augments the tooling in specific ways to address the traceability, modeling, and analysis challenges of themes 2, 3, and 7.

Continue work on specific technical attributes, focusing on the challenges of attributes that tend to defy conventional testing and inspection (themes 4, 5, and 6).

Develop assessment techniques to address the requirements elicitation goals of theme 5. |
| **2016** | Elaborate and mature solutions; engage with stakeholders; conduct trial deployments. Identify and explore new areas of high-potential research | Engage with stakeholders (potentially in collaboration with SEI) to continue the baselining and criteria definition of theme 1, leading to a preliminary formulation of an alternative model based on building code ideas (themes 2, 3, and 7).

Advance efforts in technical and tooling thrusts, producing exemplar evidence-based assurance data for existing major components.

Conduct trial deployments of advanced tooling and metrics capabilities with professional development teams in partner organizations.

Advance requirements and architecture efforts, identifying candidate "emerging best practices" to support architecture-led iterative development efforts. |

Year	Focus	Key Deliverables
2017	Demonstrate and interact with baseline capability users; extend and apply additional solutions. Mature new areas of high-potential research	Demonstrate rapid recertification for one or more of the exemplar systems for which evidence is created in 2016. Develop evidence-based approaches for dynamic and resilient systems potentially with shape-shifting architectures. Engage with stakeholders to advance experimental concepts for new evidence-based approaches to "designed-in assurance support" for larger-scale component-based systems.
2018	Based on experience with existing results, identify and pursue further baseline extensions and new-idea projects	Advance the traceability capabilities in tooling to support a concept of continuous re-evaluation and reconstruction of evidence to support a model of "continuous re-certification." Enhance tool prototypes to include broader ranges of critical technical quality attributes (theme 6). Identify advances in modeling, language, and analysis to enable broad adoption of evidence-based approaches.

The *Systemic Assurance* Project transition action plan and characterization are shown in Tables 5.2-7 and 5.2-8 below.

Table 5.2-7. *Systemic Assurance* Project Transition Actions

#	Transition Action	Principles Implemented
1	Develop and apply technical analytic approaches to extant large-scale software corpora reflective of the kinds of software components in large-scale DoD and IC systems. Publish technical assessment of the effectiveness of the models and analyses.	• Plan Early
2	Consult acquisition and sustainment subject-matter experts regarding the content of the proposed meta-criteria in order to assess the significance of the individual meta-criteria and validate and prioritize them. This consultation could include both individual subject matter experts and possibly also a workshop.	• Long and Short Term • Engage Community
3	Consult experts associated with the identified baseline practices (sub-project 1) to refine and validate the team's assessment with respect to the meta-criteria. Identify challenges and successes for the individual practices.	• Plan Early • Engage Community
4	Work with requirements and architecture subject matter experts to assess particular challenges faced in developing these high level models and, in particular, managing traceability between these models and other development artifacts.	• Engage Community • Pilot Continuously

Table 5.2-8. Systemic Assurance Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Direct assessment of representative current practice guidelines, with input from OSD regarding the selection of representative practice guidelines • Extensive technical publication related to sub-projects 4, 5, 6, and 7
Progress (approval, adoption)	• Incorporation of results of all thrusts into academic curricula • Exposure and validation of meta-criteria with DoD stakeholders.

5.2.5 OTHER SERC NON-CORE FUNDED PROJECTS

During the time of the Technical Plan, the SERC has executed one non-Core-funded TS Area project as briefly described in Table 5.2-9 below.

Table 5.2-9. TS Area Non-Core Funded Projects

Project	Sponsor	Description
Software Reliability Modeling	Navy	The three primary tasks are to (1) Design and implement a software tool framework that enables the automatic application of software reliability models; (2) Analyze the software testing and reliability policies and processes within DoD to identify suitable models to optimize their efficiency while ensuring software produced is both reliable and cost effective, and (3) Conduct research on statistical algorithms that will ensure the robustness of software reliability models, including methods based on the Expectation Maximization algorithm, Bayesian Modeling, and the Maximum Entropy Principle.

5.3 SYSTEMS ENGINEERING AND SYSTEMS MANAGEMENT TRANSFORMATION (SEMT)

Traditional DoD systems engineering and management (SE&M) practices have focused on the definition and acquisition of individual standalone platforms within a relatively stable environment.   They have generally used slow, sequential processes that often commit to requirements before their development implications are fully understood. This has caused much late and expensive rework, along with brittle, hard-to-modify architectures.

However, DoD's current and future environment requires that such platforms and their human and software elements be defined, integrated, and evolved within highly complex and dynamic net-centric systems of systems and enterprises.   The need for more innovative, life-cycle-affordable systems engineering and management approaches has been recognized by the current DoD leadership in such initiatives as Better Buying Power and the proposed life-cycle strategy for the DoD Next-Generation Bomber. This requires research focused on transforming traditional SE&M MPTs to meet these current and future DoD mission needs.

> **Goal:** Transform systems engineering and its associated management approaches away from systems designed for optimal performance against a static, pre-specified set of requirements over long procurement cycles to approaches that enhance the productivity

of engineers to rapidly and concurrently develop cost-effective, flexible, agile systems that can respond to evolving threats and mission needs. "Systems" covers the full range of DoD systems of interest from components such as sensors and effectors to DoD-wide net-centric systems of systems and enterprises. "Effectiveness" covers the full range of needed system quality attributes or ilities, such as reliability, availability, maintainability, safety, security, performance, usability, scalability, interoperability, speed, versatility, flexibility, and adaptability, along with composite attributes such as resilience, suitability, and sustainability to support the desired mission performance. "Cost" covers the full range of needed resources, including present and future dollars, calendar time, critical skills, and critical material resources.

5.3.1 SEMT GRAND CHALLENGE AND CURRENT PROGRESS

The SEMT grand challenge to achieve the SEMT goal is to:

Move the DoD community's current systems engineering and management MPTs and practices away from sequential, document-driven, hardware-centric, point-solution, acquisition-oriented approaches; toward concurrent, portfolio and enterprise-oriented, hardware-software-human engineered, model-driven, set-based, full life cycle approaches. These will enable much more rapid, flexible, scalable definition, development and deployment of the increasingly complex, cyber-physical-human DoD systems, systems of systems and enterprises of the future.

In keeping with its central position among the four SERC thematic research areas in Figure 3-1, the SEMT research area includes collaborative efforts with the other three SERC research areas with respect to their Grand Challenges. This collaboration provides SEMT with greater understanding of how its research efforts can help address their Grand Challenges, and provides SEMT with insights on how its research results can span multiple Grand Challenges.

An example of such collaboration is SEMT's research support of the ESOS Area Grand Challenge of creating SE principles and MPTs for SoS SE that generate affordable and overwhelming competitive advantage over its current and future adversaries. SEMT's research results in cost estimation of SoS SE effort, combined with its results in SysML parametric architecture modeling and previous research efforts in the *Requirements for Net-Centric SE* Project conducted before the start of this Technical Plan, have been integrated to provide SoS SE cost estimation capabilities for affordable SoSs.

A further example involves SEMT's research support of the TS Area Grand Challenge of achieving much higher levels of system trust for the increasingly complex, dynamic, cyber-physical-human net-centric systems and systems of systems of the future. A workshop involving the TS *Systems Assurance* Project and the SEMT *Systems Qualities Tradespace and Affordability* Project has led to collaborative efforts in identifying and quantifying the synergies and conflicts among strategies for assuring security and safety qualities and strategies for achieving affordability, flexibility and mission assurance qualities.

Additional examples involve SEMT's research support of the HCD Area Grand Challenge of dramatically accelerating the professional development of highly capable systems engineers and technical leaders in DoD and the defense industrial base. One example cited above is SEMT's simulation-based research on using Agile-Lean-Kanban methods to help DoD and industry SEs prioritize and accelerate rapid DoD responses to new threats and opportunities. Other examples include the previous SEMT *Graphical*

ConOps Project research and the current *Interactive Model-Centric SE* Project, both focused on how to better support human visualization and decision support in defining and developing complex cyber-physical-human systems.

SEMT has combined insights from these collaborations and support of its OSD, Air Force, Army, Navy and DoD Agency research sponsors to formulate and create stronger SE and management foundations for addressing the SEMT Grand Challenges above. These foundations include set-based design of DoD systems, quantifying system qualities and system risks, an ontology for clarifying the complexities of system qualities and their interactions, and methods for evidence and risk-based decision support for evolutionary, concurrent SE and system development projects. All of these efforts continue to evolve and identify further challenges, as described in the future plans below.

5.3.2 STRATEGY TO ADDRESS THE SEMT GRAND CHALLENGE

Successfully executing the following strategies will make significant progress towards addressing the SEMT Grand Challenge:

1. *Make Smart Trades Quickly:* Develop MPTs to enable stakeholders to be able to understand and visualize the tradespace and make smart decisions quickly that take into account how the many characteristics and functions of systems impact each other

2. *Rapidly Conceive of Systems:* Develop MPTs that allow multi-discipline stakeholders to quickly develop alternative system concepts and evaluate them for their effectiveness and practicality

3. *Balance Agility and Assurance:* Develop SE MPTs that work with high assurance in the face of high uncertainty and rapid change in mission, requirements, technology, threats, and other factors to allow a system to be rapidly acquired and responsive to both anticipated and unanticipated changes in the field

4. *Align with Engineered Resilient Systems:* Align research to both leverage the research and technology results of the Engineered Resilient Systems (ERS) program, and contribute to it; e.g., ERS efforts to define new approaches to tradespace.

Recall that, for the SERC, *development* of an MPT includes validation and transition.

Four current Core-funded SERC research programs have been implementing these strategies:

- Affordability and Value in Systems
- Quantitative Risk
- Interactive Model-Centric Systems Engineering
- Agile Systems Engineering

In addition, SEMT has been successful in attracting complementary funding from the Air Force Space and Missile Command, the Army Engineer Research and Development Center, several Navy organizations, the Marine Corps, and the National Science Foundation, all of which extend and experimentally apply the capabilities developed under Core funding.

5.3.3 AFFORDABILITY AND VALUE IN SYSTEMS PROGRAM

The *Affordability and Value in Systems* Program has been underway since 2014. It will continue to focus on improving DoD's ability to deal with System Qualities (SQs), also known as Non-Functional Requirements and *ilities*. Its analysis of the current state of the SQs art and practice has identified some serious shortfalls in their structure and coverage, which translate into serious sources of DoD program risk.

This program pursues the Grand Challenge of performing ilities tradespace and affordability analysis for cyber-physical-human systems and SoSs in a portfolio and enterprise context. It integrates current strengths in physical-systems tradespace analysis and information-systems tradespace analysis. It pursues both basic research on the foundational relationships among ilities, and applied research on the pilot application and evolution of ilities tradespace and affordability MPTs within key DoD application domains, including full-coverage cyber-physical-human total ownership cost estimation models addressing the new characteristics of future DoD systems, systems of systems, portfolios, and enterprises.

This research program primarily implements SEMT Strategy 1 above, *Make Smart Trades Quickly*. Table 5.3-1 offers a description of the *Systems Qualities* Project (SQ), the one current Core-funded project in the *Affordability and Value in Systems* Program.

Table 5.3-1. Projects in the *Affordability and Value in Systems* Program

Project	Started	Purpose	Primary SEMT Supported Strategies
Systems Qualities	2012	Pursue the Grand Challenge of performing ilities tradespace and affordability analysis for cyber-physical-human systems	1, 4

5.3.3.1 System Qualities (SQ) Project

Table 5.3-2 shows the focus and deliverables in the *SQ* Project through 2018. The project has three primary components. The Foundations component has pursued three complementary SQ representation approaches. An Ontology approach uses DoD stakeholder value propositions to organize means-ends relationships involved in satisfying the stakeholders' value propositions, and identifies sources of variability in the SQ values. A Semantic approach identifies change-oriented SQs in terms of the semantics of their causes, contexts, agents, and effects. A Formal-Methods approach uses precisely defined terms to represent the SQs and their relationships. These perspectives have been found to be complementary, and efforts are proceeding to organize them into a unified framework, and to use the framework to organize guidance for systems engineers in balancing the tradeoffs among the SQs.

The current initial form of the stakeholder value-based, means-ends framework has Stakeholder Satisfaction as its ultimate objective, and the systems engineering of successful cyber-physical-systems as its domain. It includes the stakeholder values of having current-system Mission Effectiveness (with balanced means of Speed, Delivery Capability, Accuracy, Usability, Scalability, and Versatility); current-system Efficiency (with balanced means of Cost, Duration, Personnel, and other Scarce Quantities, Producibility, and Supportability); current-system Dependability (with balanced means of Reliability, Availability, Maintainability, Safety, Security, Privacy, Robustness, and Survivability); along with future-

system Flexibility (with balanced means of Modifiability, Adaptability, and Composability). Further SQs such as Extendibility, Understandability and Testability are lower-level means supporting one or many of the means above.

Table 5.3-2. *System Qualities* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Research and develop basic system qualities (SQs) concepts and framework. Explore early MPT applications and interoperability, including with ERS counterparts.	Basic SQ concepts and framework. Results of early MPT applications and Valuing Flexibility approaches. Initial definition of integrated lifecycle cyber-physical-human system cost model.
2014	Explore integration of multi-view SQ ontology definitions. Elaborate SQ concepts and framework in key areas; e.g., SoSs, set-based design. Hold community workshops on next-generation cost model elements.	Multi-view SQ ontology definition papers. Results of broader and deeper MPT applications. Initial need/data prioritization of next-gen cost models for software, SE. Early software cost estimation, metrics manual v0.5.
2015	Integrate SQ ontology views into unified SQ Ontology; prototype initial support tools. Increasingly scalable and interoperable SQ MPTs, set-based design aids. Next-generation SE and software cost models defined; initial data collection.	Mature SQ Ontology Framework. Results of increasingly scalable and interoperable MPT applications. Exploratory application of set-based design concepts with the Army Tank and Automotive Research, Development, and Engineering Center (TARDEC) and the Naval Sea Systems Command (NAVSEA). Publication of Early Software Cost Estimation and Metrics Manual.
2016	Experimentally apply, refine unified SQ Ontology, and associated support tools. Elaborate Synergies and Conflicts matrix. Initial research in automated diagnosis of SQ levels. Experimentally apply, refine scalable, interoperable MPTs, set-based design aids. Explore domain-specific extensions, collaborations with other initiatives. Initial calibration of Next-Generation Cost Models; use in extensions to full life-cycle models.	SQ Analysis Guidebook v 1.0, associates support tools. Beta-test versions of SQ Synergies and Conflicts analysis tools. Scalable and interoperable SQ MPTs. Initial calibration of Next-Generation Cost Models. Initial exploratory full life cycle cost estimation model.

Year	Focus	Key Deliverables
2017	Experimentally apply and refine SQ Ontologies and Synergies and Conflicts support tools. Prototype wiki-based Qualipedia. Use as basis for research and development automated Synergies and Conflicts analysis and diagnostic tools. Increasingly scalable and interoperable MPTs. Further set-based design results and applications. Guidebook-based outreach and educational initiatives.	New-idea-extended SQ concepts and framework. Results of increasingly scalable and interoperable MPT applications. Extended multi-domain lifecycle cyber-physical-human system cost model, SQ Analysis Guidebook v 1.5. Initial Guidebook-oriented courseware.
2018	Evaluate, extend, and refine Qualipedia, initial automated S&C analysis and diagnostic tools. Converge unified approach to set-based design. Extend results to portfolio and enterprise levels. Productize Qualipedia-based educational technology, disseminate via short courses for DoD, faculty, industry.	Initial production-grade Qualipedia, including initial portfolio and enterprise extensions. Scalable automated Synergies and Conflicts analysis and diagnostic tools. Qualipedia-based courseware, initial usage at Air Force Institute of Technology, Naval Postgraduate School, DAU, SERC, and other universities.

The second primary component involves extending and integrating existing SQ MPTs to better support DoD cyber-physical-human SQ analysis. This includes developing more service-oriented and interoperable versions of current SERC SQ MPTs; developing approaches for better integrating MPTs primarily focused on physical, cyber, or human system SQ analysis; efforts to modify and compose existing SERC SQ MPTs to better interoperate with each other and with counterpart MPTs in the ERS community and elsewhere; and efforts to apply the MPTs to the ilities tradespace and affordability analysis of increasingly challenging DoD systems.

The third primary component focuses on affordability analysis. It addresses the challenges of cost estimation for the next generation of DoD systems in support of the DoD emphasis on affordability in the BBP memoranda. These challenges include costing of more incremental and evolutionary development approaches, of increasingly interdependent systems of systems, of agile development of rapidly fielded systems, of increasingly autonomous systems, and of the tradespace among development costs, operations and sustainment costs, and the costs of achieving higher or lower levels of system qualities.

The *SQ* Project transition action plan and characterization are shown in Tables 5.3-3 and 5.3-4 on the next page.

Table 5.3-3. *SQ* Project Transition Actions

#	Transition Action	Principles Implemented
1	Engage collaborative organizations in DoD (Army Engineer Research and Development Center, TARDEC; Naval Air Systems Command, NAVSEA, Marine Corps, Air Force Aeronautical Systems Center and Space and Missile Systems Command); Industry (major aerospace companies, cost model proprietors), FFRDCs (Aerospace, Software Engineering Institute); Professional/Industry Societies (INCOSE, International Software Engineering Research Network, NDIA) in exploring and prioritizing technical approaches	• Engage Community
2	Organize project into top-priority focus areas: SQ Ontology and Guidance; SQ Models and MPTs; Cost and Schedule Modeling	• Plan Early • Engage Community • Balance Long and Short Term
3	Develop interoperable, service-oriented models and MPTs: converged general, change-oriented, and formal ontologies; interoperable set-based design aids, SysML models and cost estimating tools; Air Force and Navy intelligence, surveillance and reconnaissance UAV models and MPTs; FACT-based multi-Service models and MPTs and Cost-Schedule estimate-range models and MPTs, emphasizing uncertainties and risks.	• Productize • Support Centrally
4	Use workshops, prototypes, and pilots to engage stakeholder communities in exploring, evaluating, and evolving increasingly relevant and practical models and MPTs	• Engage Community • Pilot Continuously

Table 5.3-4. *SQ* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Results of spearheading SQ Community of Interest in identifying, engaging, and collaborating with SQ stakeholders in exploring, evaluating, and evolving increasingly relevant and practical models and MPTs, using evidence-based 4-step plan above.
Progress (approval, adoption)	• 9 papers published in the Proceedings of CSER 2014 and 2015, and in INCOSE International Symposia 2014 and 2015. • 8 presentations at NDIA SE Symposia 2014, 2015. Several presentations at NDIA-Army Ground Vehicle SE and Technology Symposia 2014, 2015. SERC Best Student Paper 2014. • Workshops with industry and Government at Aerospace Corp. • Ground Systems Architecture Workshops 2014, 2015, • Army Practical Systems and Software Measurement Workshop 2015, • Systems and Software Cost Modeling Forums at the University of Southern California 2014, CMU-SEI 2015.

5.3.4 QUANTITATIVE RISK PROGRAM

The *Quantitative Risk* Program, which currently has one project, primarily implements SEMT Strategies 1 and 3, *Make Smart Trades Quickly* and *Balance Agility and Assurance*, respectively.

Table 5.3-5 describes the *Quantitative Technical Risk* (QTR) Project.

Table 5.3-5. Projects in the *Quantitative Risk* Program

Projects	Started	Purpose	Primary SEMT Supported Strategies
Quantitative Technical Risk (QTR)	2012	Develop a mix of near-term and long-term MPTs that quantify the technical risk programs face to support improved decision making on how to address those risks early in the program lifecycle	1, 3

5.3.4.1 Quantitative Technical Risk (QTR) Project

Table 5.3-6 shows the focus and deliverables in the *QTR* Project through 2016. The timeline beyond 2016 has not yet been established, and will be structured to build on progress through 2016. Technical risk refers to risks that originate in, have effects on, or involve in risk mitigation during system development including system configuration, architecture, baseline, technologies, design, manufacturing and/or integration. The QTR Project has two primary foci, to be addressed in parallel.

The first focus is incremental development of QTR MPTs addressing needs and gaps within the DoD acquisition Risk Management process, starting with "low-hanging fruit" then progressing to more challenging issues. The approach is to involve end-users in the services as co-developers and transition partners in order to ensure that the QTR are relevant to program risk issues; practical within the acquisition decision and information structures, processes, and temporal sequences; and can be effectively transitioned to end-users. The intent is to employ evidence-based methods to identify high-impact and high-contribution MPTs.

The second focus is fundamental research needed to develop QTR MPTs addressing challenging DoD Risk Management needs and issues. The approach is to adapt and expand promising theoretical frameworks and MPT approaches from areas outside of traditional DoD risk management, such as insurance underwriting for large-scale engineering and construction projects, real options in product design and development, and predictive analytics in insurance and business development. The scope includes risks over the entire system life cycle, peculiarities by type of system, type of acquisition, type of cause, type of causal chain, and types of mitigation strategies.

Table 5.3-6. *Quantitative Technical Risk* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Framing the issues, opportunities and technical approaches for relevant, practical QTR MPT near- and long-term research, development, validation and transition	Research framework of near- and long-term risk issues & potential QTR MPT for DoD acquisition. Findings from investigation of complexity theory for acquisition program risk management. List of approaches from outside traditional DoD acquisition. Plan for incremental development, validation and transition. Identification of potential case study systems and data sources. Outlines of strategies toward developing an adaptable integrated risk management framework, and transitioning MPT to end-user systems.
2014	Incremental development, validation and transition of QTR MPT in parallel with longer-term research for additional QTR MPT.	Data for one or more historical systems and acquisition programs for use in case studies. Documentation of one or more initial QTR MPT harvesting "low-hanging-fruit", with case studies applying the initial QTR MPT to a historical acquisition program. Technical interface specifications and coordination milestones toward transition initial QTR MPT to a service SE and risk management system. Identification and assessment of "flexibility and adaptability" strategies and risk-hedges (real option) in DoD acquisition. Identification and assessment of Risk Breakdown Structures, Risk Factor Analysis and Risk Estimating Relationships (for predictive analytics) for DoD programs.
2015 – 2018	Pilot application, verification and validation. Methods to improve visibility of risks through CDRL data reporting Continuing refinement of QTR MPT in parallel with longer-term research on QTR MPT on risks in specifications for software intensive and complex cyber-physical systems.	Documentation of provisional QTR MPT and justification/derivation. Assessment and documentation of pilot application to a Major Defense Acquisition Program from Preliminary Design Review through Functional Configuration Audit. Community engagement workshops. Recommendations for Contract Data Requirements List content and schedule language to improve visibility into risk exposure. QTR MPT for risk leading indicators and underlying theory addressing errors of omission and commission in specifications for software intensive and complex cyber-physical systems.

The *QTR* Project transition plan and characterization are shown in Tables 5.3-7 and 5.3-8 on the next page.

Table 5.3-7. *QTR* Project Transition Actions

#	Transition Action	Principles Implemented
1	Engage members of the risk management community in discussions and workshops to identify high-priority gaps in risk management capabilities, methods, procedures, and tools, and to examine progress	• Engage Community • Pilot Continuously
2	Engage collaborating agencies, specifically the TARDEC Risk Management Group, to refine, develop, and verify suitability of Risk Leading Indicators for major acquisition programs and technology demonstrator programs	• Engage Community • Pilot Continuously
3	Discriminate between near-term opportunities for practical Risk Leading Indicators from challenging risk sources for longer-term research (e.g., risk metrics for errors of omission and commission the early specifications of software-intensive and cyber-physical systems)	• Long and Short Term
4	Conduct a pilot application of Risk Leading Indicators with a current Army major acquisition program to test and demonstrate practicality with information available during development, value and relevance to the program	• Pilot Continuously • Engage Community
5	Formulate recommendations for Contract Data Reporting schedule and content that would improve visibility into program risk exposure	• Productize

Table 5.3-8. QTR Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Active engagement with the community in developing, piloting, and assessing the research products with evidence based assessment
Progress (approval, adoption)	• Extensive collaboration with TARDEC on program risk assessment. • Several presentations at NDIA-Army Ground Vehicle SE and Technology Symposia 2014, 2015.

5.3.5 INTERACTIVE MODEL-CENTRIC SYSTEMS ENGINEERING (IMCSE) PROGRAM

The *IMCSE* Program will include and significantly extend the traditional focus on the modeling of system products and the use of the models to perform system qualities (SQ) tradespace and affordability analyses as described above, and increasingly use models to generate software and hardware products. The *IMCSE* Program extensions will address the modeling of system execution processes, such as operational concept formulation, and system development processes, which can also be executed to aid in the generation of system products. Further, as was emphasized in the IMCSE section of the SERC Systems 2020 Report, an additional focus on modeling the system's environment will be pursued, which is needed for performing many of the SQ tradespace and affordability analyses. Models can also improve affordability by automatically generating needed documentation, or even better by serving as the documentation itself.

Further, models can reduce or avoid system overruns and performance shortfalls by enabling more thorough Analyses of Alternatives and evidence-based decision reviews.

This research program, which currently has one Core-funded project, primarily implements all four of the SEMT strategies. It builds on an earlier project, *Graphical Concept of Operations*, and on the IMCSE project currently underway that began in late 2013. Table 5.3-9 summarizes the active project and the strategies it primarily supports.

Table 5.3-9. Projects in the IMCSE Program

Projects	Started	Purpose	Primary SEMT Supported Strategies
Interactive Model-Centric Systems Engineering	Late 2013	Use models to drive systems engineering, development, production, and evolution	1, 2, 3, 4

5.3.5.1 Interactive Model-Centric Systems Engineering Project

Models have significantly changed SE practice over the past decade. Most notably, model-based systems engineering (MBSE) methods and tools are increasingly used throughout the entire system lifecycle to generate systems, software and hardware products, and replacing labor-intensive and error-prone documentation-based processes with model-based ones. While substantial benefits have been achieved, the most impactful application of models in SE has yet to be realized. Truly transformative results will only come through intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints. The *IMCSE* Project seeks to enable this transformation.

The complexity and socio-technical nature of contemporary systems/SoSs drives an urgent need for a more powerful integration of humans and technologies. Early concept decisions have always been critically important, and with continuously evolving SoSs having long life spans, such decisions are now made throughout the entire life cycle. Soft factors become increasingly influential. For example, trust in model-based data sets and decisions are in part determined by the chosen model itself as perceived by specific decision makers. The timescale of making early architectural decisions is out of sync with the current model-based systems engineering capabilities and decision environments. New algorithms and novel modeling approaches must be discovered to accelerate technical and programmatic decision support from months to minutes; in order to effectively leverage and incorporate human knowledge and judgment, this requires an interactive capability. Much potential exists in maturing emerging novel methods for evaluating system responsiveness under complex uncertainties, to enable engineering of resilient systems. Further, as was emphasized in the SERC Systems 2020 Report, modeling the system's dynamic operational environment remains an open area of research. Forward research is informed by a recently completed SERC *Graphical Concept of Operations* Project.

The *IMCSE* Project involves three tasks initiated in 2014, followed by additional tasks in out-years.   The three tasks are:

1. **Pathfinder.** The task will investigate the current state of the art/practice in interactive model-centric systems engineering. Surveys and literature review were used to establish a preliminary picture of what is being done in practice, current MPTs, and what research has/is being performed. This informed the planning and conduct of an invited workshop to identify research opportunities, gaps and issues.

2. **Interactive Schedule Reduction Model.** This task builds on an existing prototype model (prior Defense Advanced Research Projects Agency support) for interactively exploring alternatives in the systems development process and application of resources.   The model enables rapid sensitivity analysis of various factors to determine their potential impact on program schedule. Exploratory extensions of the model will be developed and evaluated, resulting in a new prototype for pilot application.

3. **Interactive Epoch-Era Analysis.** This task involves research to extend a current approach for evaluating systems under uncertainty, Epoch-Era Analysis, through the development of an interactive capability.   The resulting prototype method and supporting tools are being applied to a case on uncertainties in mission planning and deployment support, of particular interest to the ERS program. This case application serves as a pathfinder for identifying key considerations for applicability and deployability of the method for eventual DoD use.

Table 5.3-10 shows the focus and deliverables in the IMCSE Project through 2018 aimed at addressing the three tasks above, as well as new tasks in out-years. In 2014, the "Pathfinder" task investigation identified synergistic research opportunities. Beginning with the initial 2014 workshop, periodic targeted workshops will be convened with the intent of examining ongoing research that can be leveraged in the SERC research efforts, and involving the broader community in creating – and realizing – the vision and research agenda for the *IMCSE* project and the broader program.

Table 5.3-10. *IMCSE* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	New start	
2014	Pathfinder task with collaborative research discovery; exploratory extensions to an existing development schedule reduction model; exploratory piloting and interactive extensions to Epoch-Era method	*Pathfinder Task:* Workshop to explore issues and opportunities, with report on workshop results. Pathfinder task report, with findings of research opportunities, gaps, and issues. Out-year research plans based on pathfinder results. *Interactive Schedule Reduction Model:* Exploratory extensions implemented and evaluated. Report on exploratory schedule model. Prototype model for pilot application. *Interactive Epoch-Era Analysis:* Exploratory research to develop interactive capability, with demonstration via a mission planning support application case. Report on exploratory research and case application.
2015	Initiate multi-year research plans based on Pathfinder results, including 2014 follow-on for one or both of the exploratory research tasks. Assess results individually and comparatively.	*IMCSE Project Applications:* Based on Pathfinder results, select and initiate one or more additional tasks, and increase SERC member collaboration in tasks. Report will document the maturation of the MPTs for each of these projects, with comparative results.
2016	Increasing maturation of *IMCSE* MPTs and enabling environments, leading to adoption by user community; extend *IMCSE* scope via increased collaboration of universities and broader user community. Exploration of further new-idea projects.	*IMCSE MPT Implementations and Impact Assessments:* Continued maturation and implementation of IMCSE MPTs, with enabling environments. Ongoing study of impacts resulting in a comprehensive report of progress, results, and opportunities.
2017 – 2018	Increasing maturation and synthesis of IMCSE MPTs and enabling environments, leading to adoption by user community; sustain and increase collaboration of universities and broader user community. Step-ups of new-idea tasks.	*IMCSE MPT Synthesis Impact and Effective Practice Assessments:* Continued maturation, synthesis and implementation of IMCSE MPTs, with enabling environments. Ongoing study of real-world impacts to identify successful practices. A comprehensive report of impacts and insights, with guidance on practice.

The *IMCSE* transition action plan and characterization are shown in Tables 5.3-11 and 5.3-12 below.

Table 5.3-11 *IMCSE* Project Transition Actions

#	Transition Action	Principles Implemented
1	The *IMCSE* Project has been developed using three complimentary thrusts (foundations, fundamentals, applications) with different timescales, to have impact on the long term, near term and the present. An over-arching project goal is to build a community of interest around IMCSE.	• Plan Early • Balance Long and Short Term • Engage Community
2	An *IMCSE* Pathfinder Workshop engaged members of the community in characterizing state of the art/practice, identifying research needs, and envisioning the model-centric environment of the future. A workshop report was published and distributed. Efforts to gather research needs and develop broader collaboration on longer term research agenda have been initiated.	• Engage Community • Balance Long and Short Term
3	A proof-of-concept prototype for the Interactive Schedule Reduction Model was completed, demonstrated to practitioners, and software made available through a website.	• Engage Community • Pilot Continuously • Productize
4	Prototype visualization tools for Interactive Epoch-Era Analysis have been piloted with students and demonstrated to practitioners. An interactive demonstration prototype is being made available online to gain feedback, with continuing updates planned as the MPT matures.	• Engage Community • Pilot Continuously • Productize
5	Model trade-off case studies for value models have been completed and made available. Performance model and cost model trade-off cases will be developed and made available.	• Productize • Pilot Continuously
6	*IMCSE* has held knowledge exchanges, collaborated with, and discussed future pilot opportunities with several other universities, FFRDCs and non-profits, and government agencies.	• Productize • Engage Community

Table 5.3-12. *IMCSE* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• *IMCSE* Technical Reports and the *IMCSE* Pathfinder Workshop Report are available to the SERC community. Once completed, the demonstration prototype with documentation can be accessed freely and downloaded. A second demonstration prototype is in implementation.
Progress (approval, adoption)	• *IMCSE* has effort has resulted in 2 technical reports, 3 published conference papers, 5 conference presentations, and held one workshop (with report published). • An *IMCSE* paper received the 2014 SERC Best Student Paper Award and another *IMCSE* paper received the CSER 2015 Best Academic Paper Award

5.3.6 AGILE SYSTEMS ENGINEERING PROGRAM

Agile, lean, and other adaptive processes and governance mechanisms are key to meeting the SEMT Grand Challenge. To be adaptive, systems engineers must have MPTs to identify, understand, and quickly react

to issues raised by increasing reliance on systems of systems, interoperability between legacy and new capabilities, evolving requirements throughout the development lifecycle, and the changing economic and political factors that undergird and enable system development. At the same time, the human relationships that anchor good decision-making depend on enhanced visibility into increasingly deep supply chains, constraining contractual relationships, and murky component systems. Identifying and validating management and governance strategies and mechanisms that inherently support negotiation, collaboration, and shared outcomes are a major goal of this research.

Adaptive processes can reconcile the differences between systems engineering and software engineering activities, and integrate them to achieve more reliable flow and faster delivery of value to the success critical stakeholders. Software enables rapid deployment of enhanced or new capabilities while maintaining continuous overall system operations. Currently, software development processes do not operate seamlessly with SE processes. As an example, the ability for software to provide incremental capability requires adaptation of SE MPTs to enable modularity, flexibility, continuous integration, and incremental verification and validation. The *Agile SE* Program seeks balance between the integrity and stability of traditional SE and the rapid response and immense flexibility of software engineering. Having gained significantly better understanding of the issues and concerns facing SE management and government, the two projects, *Kanban in SE*, and *Agile SE Enablers and Quantification* work closely together.

With a mix of Core and non-Core funding in 2015 to support the development of the Demonstration and Analysis Tool for Adaptive Systems Engineering Management (DATASEM), the two current projects have worked closely in the definition and development of the DATASEM environment. The *Agile SE Enablers and Quantification* Project undergirds and drives a broader scope of adaptive SE and SoSE research activities. Both will share participation in and leverage INCOSE's Agile SE Life Cycle Model Fundamentals project[14]. As illustrated in Figure 5.3-1, the identification of SE enablers will be a coordinated partner with the *Kanban in SE's* DATASEM evolution and transition process.

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[14] See http://www.incose.org/newsevents/news/2014/11/17/domain-independent-agile-se-life-cycle-project.
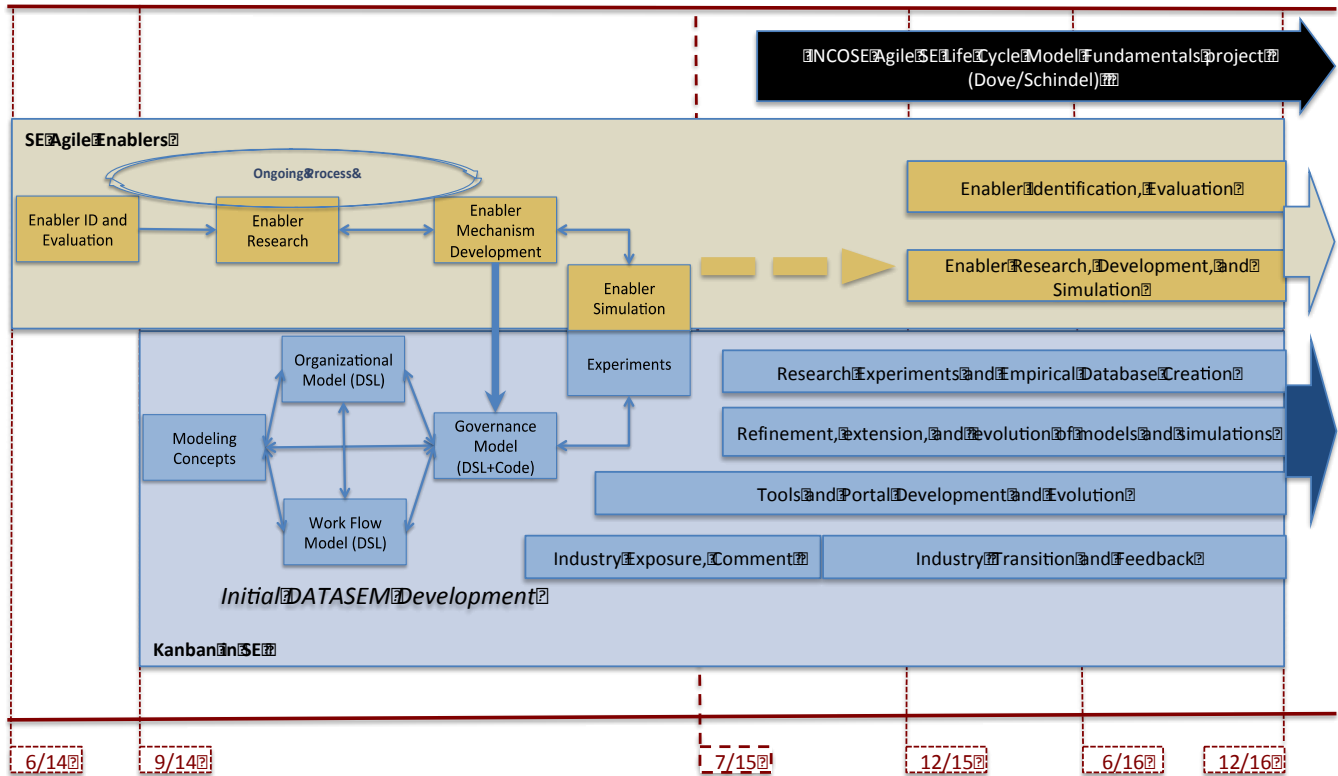
Figure 5.3-1. Agile SE Management Project Updates

Table 5.3-13 offers a description of the projects—completed, completing, and new—and the strategies they primarily support.

Table 5.3-13. Projects in the *Agile* SE Program

Project	Started	Purpose	Primary SEMT Supported Strategies
Kanban in SE	2010	Exploration of applicability of Kanban methods to complex system evolution where development is primarily through capability enhancement and new features added to an existing system. Providing tools that support experimentation, validation, and transition of defense programs to effective adaptive SE management and governance approaches. Development and evolution of DATASEM, and extending the DATASEM scope to evolving operational environments.	2,3,4
Agile SE Enablers and Quantification	2008 and continued in 2012	Identifying and employing research that can inform and improve agile (adaptive) SE, drawing on the SERC RT-34 *Expediting SE* effort and its initial model quantifying agile schedule compression. Providing a growing set of management and governance mechanisms, technical processes, work flows and simulation capabilities that reflect new adaptive systems engineering enablers and practices.	1,2,3,4

5.3.6.1 *Kanban in SE* Project

Initially motivated by the ineffectiveness of integrated master schedules in rapidly changing operational environments and the success of Kanban approaches for the knowledge work of software development, the project has expanded to investigate the applicability of Kanban as well as that of other adaptive governance mechanisms. The initial Kanban scheduling system (KSS) networks described in SERC RT-35 sought a way to prioritize engineering tasks based on SoS or complex system capability priorities and task interdependencies by selecting value-adding features first, reducing wait time for scarce engineering specialties, and minimizing time wasted on context switching by overloaded resources. The KSS network concept provides two valuable side effects. First, the implementation of the network supports critical conversations about schedule and value decisions by the appropriate people at the right time and nearest the actual implementation. Second, the network significantly improves executive and systems engineering visibility into the status of multiple independent development organizations.

Research in 2014-2015 developed DATASEM, a simulation generator and test bed for experimenting with the KSS-introduced and related adaptive governance mechanisms. DATASEM uses a set of Domain Specific Languages (DSLs), created to describe organization, work flow, and governance models, to generate simulations for experimentation and demonstration. Initial versions of DSL have been completed, and translation and implementation code developed for simulating the core KSS mechanisms using an agent-based simulation facility (Repast). Tools to develop experiments, define mechanisms, and display simulation results are also being developed. A first generation DATASEM suite was completed in 2015.

The first generation DATASEM Suite will provide significant functionality and information. However, only a subset of possible models and mechanisms will have been developed, and the DSLs and infrastructure can be extended to address a variety of additional investigations. There are numerous opportunities to

extend the capabilities and enhance the usefulness of DATASEM including a wider range of agile methods, incorporating technical debt, as a demonstration vehicle for the impact of changing governance mechanisms, modeling of acquisition processes; and identifying, evaluating and implementing new mechanisms and approaches that emerge from these research efforts. For example:

- DATASEM has attracted significant attention from the system of systems community as a way to not only investigate, but also demonstrate the impact of change on both existing and adaptive governance mechanisms, and to measure the effectiveness of various combinations. Adding to the DSL and infrastructure support for modeling organizational negotiation and communication activities related to SoS governance can improve management understanding of the critical nature of such activities to effective governance.
- DATASEM could be applied to acquisition governance processes to develop and test alternative governance approaches and to identify and create ways to mitigate incompatibilities between adaptive and traditional governance mechanisms. Industry has suggested the project consider the concept of technical debt in the DATASEM models and as a significant attribute for characterizing particular configurations of workflow, organization, and governance, leveraging other SERC research in this area.
- INCOSE is conducting a broad analysis of the agile systems engineering life cycle. This should identify additional mechanisms and approaches that are not directly supported by the first generation and provides a way of validating some of the first generation mechanism simulations.

Table 5.3-14 shows the focus and deliverables in the project through 2018.

Table 5.3-14. *Kanban in SE* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Studying on-demand scheduling systems and adapting the concept to SE	KSS concepts; RT-35 Kanban in SE reports and papers; Kanban in SE industry working group
2014 – 2015	Building the first generation DATASEM Suite	Fully operational stand alone and web-available versions
2016	Building an empirical database and components to support further experimentation and evolution; extending application contexts; continuing SE enabler identification, evaluation, and implementation in DATASEM	Refinements of first generation components; New DATASEM components to handle new mechanisms including technical debt as a comparative indicator, acquisition activities; New versions of Quantitative Schedule Acceleration Model (QSAM) with expanded applicability; additional domain coverage
2017 – 2018	Expansion of user community and databases	Expand experimentation and use for transition of industry and government to more adaptive governance as appropriate

The *Kanban in SE* transition plan and characterization are shown in Tables 5.3-15 and 5.3-16 below.

Table 5.3-15. *Kanban in SE* Transition Project Transition Plan

#	Transition Action	Principles Implemented
1	Work in direct response to customer needs with the goal of improving SoS SE performance. Industry and government volunteers involved in the definition and substance of the concept developed through an industry-working group.	• Plan Early • Engage Community
2	The primary deliverable designed to validate the concepts and provide a persistent and evolving tool to support transition by allowing adopters to "try before they buy".	• Balance Long and Short Term • Pilot Continuously
3	As the tool is evolving, maintaining contact with industry and government through NDIA, and INCOSE. Publishing and participating in conferences and workshops to both demonstrate the capabilities and gather improvement ideas.	• Plan Early • Engage Community
4	The toolset and environment will be hosted by the SERC and available to the public. It will also be available as a package for use within restricted environments.	• Support Centrally • Productize

Table 5.3-16. *Kanban in SE* Project Transition Plan

Characteristic	Evidence
Readiness (relevance, practicality)	• The 2014-2015 activities produce an executable, deployable, and useful tool. • The 2016 activities will implement an empirical research program validating the concepts, measuring sensitivities, comparing results to pilots and establishing whether the tool meets either or both of the transition support and research goals; it will also expand the usefulness and range of users by integrating the tool with the Experience Accelerator.
Progress (approval, adoption)	• *Kanban in SE* has published 8 conference papers, 2 articles, 3 technical reports and held 2 workshops with industry and government participants • Sponsor demonstrations of DATASEM capabilities resulted in both positive feedback as well as additional ideas for expanding the capabilities • Industry and government members of the INCOSE Agile SE Life Cycle Model Fundamentals Project have specifically asked DATASEM and Agile Enablers to be a part of that work • DATSEM integration with the Experience Accelerator was suggested independently by both the sponsor and industry

5.3.6.2 Agile SE Enablers and Quantification Project

The *Agile SE Enablers and Quantification* Project was originally established to continue work on MPTs identified in the RT-34 and RT-35 efforts. It also established a method for evaluating the promise of new methods and techniques. The conducted research led to the improvement and extension of QSAM and directly supported the definition of the methods and mechanisms implemented in the first generation DATASEM suite. It will continue to identify new possibilities, but will concentrate on the evolution of these two central research tools.

In 2015, the QSAM was expanded to include more specific agile and lean drivers to better capture the activities associated with their use in SE. New datasets were identified and used to further calibrate the model. Core funding for this work has been suspended.

Table 5.3-17 shows the focus and deliverables in Agile SE Enablers through 2015.

Table 5.3-17. Agile SE Enablers Project Timeline

Year	Focus	Key Deliverables
Pre – Core	MPTs in software	MPT reports and papers; RT-35 phase 1 work; RT-34 work; support of INCOSE Agile SE Working Group
2014 – 2015	Fundamentals of agility	White papers: SE as a service concept. Governance, organizational and contracting requirements for implementing agile SE. Quantitative schedule acceleration model extensions, calibration, behavioral analysis.

5.3.7 SEMT AREA NON-CORE FUNDED PROJECTS

During the time of the Technical Plan, the SERC has executed seven non-Core-funded SEMT Area projects as briefly described in Table 5.3-18 below. One additional project has been omitted because of its sensitivity, and one project, *Kanban for SE*, received funding from the Intelligence Community to complement Core funding.

Table 5.3-18. SEMT Area Non-Core Funded Projects

Project	Sponsor	Description
Virtual Collaboration Environment for Conducting Project Design and Tests	Marines	Enhance the FACT tool to integrate with existing simulation tools in order to be able to drive additional capabilities into the simulation tools
FACT Amphibious Combat Vehicle Analysis	Marines	Enhance tooling to conduct tradespace analysis for large amphibious combat vehicles
FACT Portfolio Management	Marines	Enhance the FACT tool to be able to identify system components and correlate them, with their identified attributes, into a set of capability options
SE Modeling & Simulation Integration Framework	Army	Review existing and emerging models, frameworks and standards relevant to modeling the SE workflow for modeling and simulation integration in the digital thread; select a framework and develop preliminary guidelines to model and document the digital thread; and develop a preliminary model of how to transform an organization so it can use the digital thread approach
ERS Tradespace	Army	Develop decision support methods and a tradespace toolset framework architecture in support of Engineered Resilient Systems

Project	Sponsor	Description
Kanban for SE	IC	A second sponsor supplemented funding for the Core-funded *Kanban for SE* Project to support more automation than would have been possible with just Core funding.
Transforming SE Through MBSE	Navy	Assess the technical feasibility of a radical transformation of acquisition through a more holistic model-centric engineering approach.

5.4 HUMAN CAPITAL DEVELOPMENT (HCD)

Over the last decade, DoD and the defense industrial base have often cited a shortfall in the quantity of systems engineers and in the knowledge, skills, and abilities of those systems engineers[15,16]. Not only is there a critical shortage of systems engineers, but the skill sets and capabilities of these engineers need to rapidly expand to address the growing complexity in the systems they are attempting to engineer. Systems Engineering Vision 2025[17] presents a future view of SE. That report highlights several areas that directly impact Human Capital Development.

Systems Engineering is not only for those with the title of "Systems Engineer". Systems skills are essential for systems decision makers, technical leaders and all engineers. All leaders and those making decisions about systems need to be systems thinkers. Systems thinking skills need to be developed long before graduate studies and should be introduced as early as kindergarten through high school. All engineers should have some education and training in systems and SE. While undergraduate curricula are already full, these skills can be introduced and distilled in cornerstone and capstone projects. Finally, systems engineers need to be well versed in a broad set of socio-technical and leadership skills, serving as a central, multi-disciplinary focal point of systems development with stakeholders of all types.

The Human Capital Development (HCD) research area directly targets the aforementioned shortfalls and challenges.

> **HCD Area Goal:** Ensure a competitive advantage through the availability of highly capable systems engineers and technical leaders for the DoD and the defense industrial base

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[15] See http://www.ndia.org/Divisions/Divisions/SystemsEngineering/Documents/Studies/Top%20SE%20Issues%202010%20Report%20v11%20FINAL.pdf.

[16] See http://www.ndia.org/Advocacy/PolicyPublicationsResources/Documents/WSARA-Public-Law-111-23.pdf.

[17] See http://www.incose.org/docs/default-source/aboutse/se-vision-2025.pdf?sfvrsn=4.

5.4.1 HCD GRAND CHALLENGE AND CURRENT PROGRESS

The HCD Grand Challenge to achieve the HCD goal is to:

> Discover how to dramatically accelerate the professional development of highly capable systems engineers and technical leaders in DoD and the defense industrial base and determine how to sustainably implement those discoveries

Significant HCD progress has been made through a mix of Core-funded and non-Core funded projects. Successes in the *Evolving Body of Knowledge* Program include:

1. *The* BKCASE Project has made great strides in organizing information and making it globally accessible and available. This project was successfully completed and transitioned just as this Technical Plan was approved. Since September 2012, there have been nearly 1,000,000 visits to articles on the Systems Engineering Body of Knowledge (SEBoK) wiki[18] and many universities have adopted all or part of the recommendations found in the Graduate Reference Curriculum on Systems Engineering (GRCSE)[19]. Their continued use and evolution will provide an up-to-date source for systems knowledge.

2. As described in Section 5.5.2.2, the SERC Innovation and Demonstration Lab is beginning to make research resources such as publications, tools and data sets available for education and the advancement of systems research. This is an area that has great promise as an enabler for the advancement of systems research and knowledge.

3. The Helix project is showing success in understanding what enables systems engineers to be effective, how systems engineers mature, and in characterizing the systems engineering workforce. Several organizations have begun using Helix for their workforce improvement efforts.

Finally, as observed through *BKCASE*, there is a great need for SE case studies to provide real life lessons on the "how" of SE. To date, it has been difficult to acquire the program data to provide this research with the desired impact. This is a gap that will need to be resolved.

The *Experience Acceleration (EA)* Program has continued to mature and now has a variety of capabilities that should support experiences in numerous domains and in several different single and multi-player modes. There is a great potential for this technology to advance the strategic objective of educating and training faster. Limited pilots have been conducted that both show the potential of the technology and have served to provide feedback in its subsequent development. In addition, a set of prototype tools have been developed that show the potential for tailoring existing experiences and developing new ones. Critical work moving forward is in learning evaluation and the validation of the hypothesis that technology can be used to accelerate learning for systems thinking and engineering. This can be facilitated through the use of the EA in Collaborator university courses and training. In addition, it will be necessary to show that experiences can be efficiently created and modified by the non-research community. Finally, a sustaining open source community is needed to ensure that Experience Acceleration experiences and technology can be supported for widespread deployment.

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[18] See http://www.sebokwiki.org.
[19] See http://www.bkcase.org.

The *Systems Engineering and Technical Leadership Education* Program continues to make strides improving technical leadership and SE education, primarily with non-Core funds. The *Engineering Capstone Marketplace* Project (which is funded by a mix of Core and non-Core funds) is the evolution of research begun in 2010, which showed that a multidisciplinary senior capstone project could enhance development of SE competencies and increase interest in SE. The challenge is in scaling this approach nationwide, to have impact on how thousands of students are taught engineering across the US. The *Technical Leadership* Project also began in 2010 to evaluate the hypothesis that the technical leadership capabilities of high potential, senior DoD systems engineers and technologists could be accelerated through an educational program in technical leadership. This initial research has spawned several efforts for DAU and the Army. The former research resulted in the creation of an innovative approach to educating technical leaders through three lenses: systems, business, and enterprise. That approach was captured in courses have been prototyped, piloted and are being transitioned to DAU. Again, the challenge is in expanding the offering of these courses to broaden their impact.

There are a number of additional remaining gaps that will be necessary to address the HCD Grand Challenge. Some of these include: how to better capture the knowledge of systems engineers who are nearing or in retirement, how to more closely couple research results to their dissemination in education, and how to expand systems education into kindergarten through high school.

5.4.2 STRATEGY TO ADDRESS THE HCD GRAND CHALLENGE

Successfully executing the following strategies will make significant progress towards addressing the HCD Grand Challenge:

1. *Create and Provide Easy Knowledge Access:* Make it easy for systems engineers to understand the SE discipline and to access the information needed to expertly perform SE so that the workforce can master the most important competencies

2. *Educate and Train Faster:* Develop innovative approaches and technology to educate and train systems engineers and systems teams at all levels, engineers, and STEM students much more rapidly, effectively and efficiently than with classical means

3. *Develop Effective Technical Leaders:* Develop innovative approaches to educate DoD technical leaders with the right mix of technical, business, and enterprise skills

4. *Improve SE and STEM Education:* Develop recommendations and systems curricula for the next generation of systems engineers, engineers and STEM students

5. *Track Progress:* Track the changes in SE workforce demographics and performance over time to understand how the workforce is improving and how improvement programs are working

Recall that, for the SERC, *development* of an MPT includes validation and transition.

Three HCD research programs directly implement the strategy:

- Evolving Body of Knowledge
- Experience Acceleration
- Systems Engineering and Technical Leadership Education

5.4.3 EVOLVING BODY OF KNOWLEDGE PROGRAM

This research program primarily implements HCD strategies 1, 4 and 5 above – *Create and Provide Easy Knowledge Access, Improve SE and STEM Education,* and *Track Progress*. It includes two current projects – Helix and SEEK. A third project – BKCASE – successfully completed at the end of 2013 as a research effort, although the SERC maintains a role as one of three stewards leading the operation and maintenance of *BKCASE* products. Table 5.4-1 offers a description of these three projects and which strategies they primarily support.

Table 5.4-1. Projects in the *Evolving Body of Knowledge* Program

Projects	Started	Purpose	Primary HCD Supported Strategies
BKCASE	2009; successfully completed at the end of 2013	Create, disseminate, and evolve the authoritative guide to the SE body of knowledge and recommendations on curricula for SE graduate programs	1, 3, 4, 5
Helix	2012	Understand the characteristics of the SE workforce and what enables them to effective and use those insights to inform workforce development of systems engineers	3, 5
SEEK	2013; suspended at the end of 2015	Capture insights from SE experts about significant program successes and failures and portray them primarily in case studies augmented by multi-media materials for easy access and use in training, education and practice	1,3,4

5.4.3.1 BKCASE Project

The *Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE)* Project is (a) identifying and making readily accessible the vast knowledge that systems engineers need to know (SEBoK) and (b) providing recommendations to the SE academic community on SE graduate curricula (GRCSE). *BKCASE* began in 2009 as a SERC-supported project led by Stevens Institute and the Naval Postgraduate School. Beginning in 2013, INCOSE and the Institute of Electrical and Electronics Engineers Computer Society (IEEE-CS) became co-stewards with the SERC to guide and promulgate the SEBoK and GRCSE. Both products undergo regular updates to reflect advances in the field and feedback from the user community. SEBoK articles have been accessed more than 1,000,000 times since Version 1.0 was released in September 2012. Several universities in the US, Europe, and elsewhere have been adopting GRCSE curriculum recommendations. The SEBoK is novel in its form of delivery (a wiki), its governance model (shared among 3 organizations), its scale (spanning the technical aspects of the discipline, how that technology is effectively adopted and used, and the underlying science on which the technology is based), and its rate of change (multiple updates annually).

No DoD research funds have been used to support *BKCASE* since the Technical Plan was published in October 2013 and there is no expectation that any such funds will be used for *BKCASE* in the future.

The *BKCASE* transition action plan and characterization are shown in Tables 5.4-2 and 5.4-3 below.

Table 5.4-2. *BKCASE* Project Transition Actions

#	Transition Action	Principles Implemented
1	From the very beginning of the project, the BKCASE team formed an alliance with INCOSE and the IEEE Computer Society to collaborate on BKCASE; that agreement led to participation from INCOSE's corporate members who contributed authors and produced buy-in for them to adopt both the SEBoK and GRCSE as strategic assets.	• Plan Early • Engage Community
2	BKCASE held a number of public events and the drafts of the SEBoK and GRCSE were widely disseminated for community review.	• Engage Community
3	The SEBoK and GRCSE were created, released, and piloted incrementally in several major releases which were reviewed through comments provided over the Internet, in workshops and other public forums, and presented at conferences. This also enabled early adopters to try draft versions within their organizations.	• Pilot Continuously • Balance Long & Short Term • Engage Community
4	The *BKCASE* Project moved from an effort led by the SERC with community engagement to a different governance model where it became one of three steward organizations. The governance approach consistently required all *BKCASE* products to be available at no cost in order to encourage broad adoption.	• Engage Community • Productize

Table 5.4-3. *BKCASE* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• The wiki format for the SEBoK has proven very practical, allowing for easy access across the worldwide systems community and has been updated twice annually for three years since its first production release, keeping it current and expanding its coverage of SE.
Progress (approval, adoption)	• Almost 20,000 people visit the SEBoK wiki every month. The IEEE Computer Society plans to revamp their Software Engineering Body of Knowledge to be structured as a wiki relying on much of the same infrastructure as was used for the SEBoK. The SEBoK has become an acknowledged strategic asset of INCOSE. Universities in Europe, Australia, and the US have explicitly acknowledged using GRCSE to update their SE graduate programs.

5.4.3.2 Helix Project

Helix began in October 2012 to examine the "DNA" of the systems engineering workforce in both DoD and the defense industrial base. The project is answering three questions:

- What are the characteristics of systems engineers?

- What enables them to be effective and why?

- What are employers doing to improve the effectiveness of their systems engineers?

Based on interviews with nearly 300 systems engineers and those who work with systems engineers, Helix developed *Atlas*, a theory of what enables systems engineers to be effective. Atlas describes the key proficiencies that impact the effectiveness of systems engineers, the several forces that impact the level of proficiency that systems engineers obtain, how the career paths of systems engineers progress, how

personal and organizational characteristics affect the evolution of systems engineers, and also provides demographic data about systems engineers, such as their typical education and how that demographic data has changed over time. The project has expanded beyond systems engineers in the defense community and is now looking more broadly at systems engineers in such commercial sectors as healthcare and information technology.

Table 5.4-4 shows the focus and deliverables in the Helix Project through 2018.

Table 5.4-4. *Helix* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Establish methodology, small-scale data collection, publish early findings	Early findings report from both DoD and the defense industrial base
2014	Large-scale data collection and analysis; begin regular publication of findings	Regular reports of findings; first version of *Atlas*
2015 – 2018	Data collection from broad commercial community and understanding of what enables other engineers to be effective when performing systems activities	Regular reports of findings; mature version of *Atlas;* book on what enables systems engineers to be effective; user communities

The Helix transition action plan and characterization are shown in Tables 5.4-5 and 5.4-6 below.

Table 5.4-5. *Helix* Project Transition Actions

#	Transition Action	Principles Implemented
1	SERC formed an alliance with INCOSE to collaborate broadly on research and then developed a specific agreement to collaborate on Helix; that agreement led to participation from INCOSE's corporate members who provide data, pilot Atlas, and aid its adoption.	• Plan Early • Engage Community • Support Centrally
2	Helix has an advisory group from the community and periodically holds workshops with that group and with others to review status, plans, and interim results.	• Engage Community
3	Atlas is being created, released, and piloted incrementally in three major releases which are reviewed in workshops and other public forums, presented at conferences, and described in peer-reviewed papers.	• Pilot Continuously • Balance Long & Short Term • Engage Community
4	Helix is gradually creating and validating artifacts to help organizations successfully apply Atlas to aid their workforce development.	• Productize

Table 5.4-6. *Helix* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Activities leading up to Atlas 0.5 (the latest release) were sufficiently useful and practical that several participating organizations have altered their workforce development approaches to accommodate Helix insights.
Progress (approval, adoption)	• Helix has published 4 technical reports, 2 conference papers, held two workshops, and submitted 4 journal articles. • Organizations beyond the defense community are participating, expanding Helix outreach.

5.4.3.3 SEEK Project

This project addresses a gap in the SE research literature: the lack of detailed case studies about SE successes and failures. The research developed its first case studies in 2014 and 2015, tailored to defense education needs. These case studies will support instruction at DAU and at the Naval Postgraduate School, the federal service academies, and other government education and training providers.

Much of SE and technical role documentation provides a description of the "who", "what" and "when". However, there is very little guidance on the "how" for these activities. Case studies are a tool that can be used to provide realism and bring the systems engineering practice to the classroom. They can be a valuable source of lessons learned and underscore the effect of decision making. The intent of this work is to provide the means to support the teaching of the "how" through the use of case studies and program artifacts. Rather than adapting a case study to a course curriculum, these cases have been selected and developed with the end result in mind, namely supporting the new DAU Reliability & Maintenance course. The new course consists of five topics covering a significant (e.g. Acquisition Category 1 and 2) Defense Acquisition program lifecycle. The approach is to create a set of two companion case studies that cover the entire program lifecycle, particularly through Test and Evaluation. To provide contrast, one of the case studies will describe a relatively successful program, while the other will cover one that was not as successful. In addition, these cases and materials will be assembled in a format that allow broad application into other Systems Engineering roles and activities.

Obtaining the desired program information has been a challenge. Program execution in years 2016 is contingent upon acquiring adequate program data or will necessitate a shift to an interview based approach. At this point, no activities are planned in 2016 pending confirmation that the necessary program data for an in-depth case study will be available.

Table 5.4-7 shows the focus and deliverables in the SEEK Project through 2018.

Table 5.4-7. *SEEK* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Form project and set up infrastructure to capture expert knowledge	None
2014	Determine areas of interest, select target programs, acquire program data, develop case study and educational materials	Two case studies and supporting educational materials.
2015 – 2018	Refine and repeat process, increasing depth of current cases or in new programs	Two case studies and supporting educational materials annually is desirable.

The SEEK transition action plan and characterization are show in Tables 5.4-8 and 5.4-9 below.

Table 5.4-8. *SEEK* Project Transition Actions

#	Transition Action	Principles Implemented
1	Engaged with DAU at onset of project to specify research outcome requirements so that it may be integrated into a DAU course being developed.	• Plan Early • Long and Short Term
2	Created informal board of advisors to review SEEK progress and provide directive feedback.	• Engage Community
3	Presented case study approach and draft of final report and deliverables to the DAU and Sponsors during research process.	• Pilot Continuously

Table 5.4-9. *SEEK* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• DAU has approved the conceptual plan for integrating SEEK results into their newly being developed Reliability and Maintainability course.
Progress (approval, adoption)	• Early SEEK deliverables will be provided to the DAU and sponsor for feedback

5.4.4 EXPERIENCE ACCELERATION PROGRAM

This research program primarily implements HCD Strategy 2 – *Educate and Train Faster*. It will include projects aimed at creating automated learning environments that simulate real world experiences of systems engineers. Those experiences will be vivid and realistic enough to significantly accelerate the learning and maturation of those systems engineers. One project will evolve the current simulation platform, making it ever more robust and capable and enabling quicker and easier construction of new experiences. Other projects will add to the current catalog of experiences, developing new experiences that use the simulation platform. Experiences will vary based on the size and types of systems being acquired, the acquisition lifecycle, the novelty of the technology being acquired, and other parameters of interest. Over the five-year period from 2014-2018, other organizations will join the SERC in improving

the experience platform and in developing additional experiences, creating a marketplace for experience acceleration. Table 5.4-10 offers a description of these projects and which strategies they primarily support. Table 5.4-11 shows the focus and deliverables in the *Experience Accelerator* Project through 2018.

This program is unusual in that the primary project, *Experience Accelerator*, has had relatively little Core funding. Moreover, relatively little Core funding is expected in the future. DAU has been and remains the primary sponsor for the effort. Other DoD organizations are expected to provide additional non-Core funding to create new Virtual Experiences beginning in 2016.

Table 5.4-10. Projects in the *Experience Acceleration* Program

Projects	Started	Purpose	Primary HCD Supported Strategies
Experience Accelerator	2010	Create the "engine" that will be used to host a wide range of experiences, develop the first virtual experiences that use the engine, and validate the experience accelerator concept through trial use. Keep improving the engine over time as a broader set of experiences are created and trialed with ever more students. Create an open vibrant community that will develop additional virtual experiences that can be shared within the defense industrial base and DoD.	2
Additional Virtual Experiences	Expected 2016 and beyond	Relying on non-Core investment, develop an increasingly broader and richer set of virtual experiences that are hosted on the Experience Accelerator engine	2

Table 5.4-11. *Experience Accelerator* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Build experience accelerator engine, first experiences, and validate concept with first students	Increasingly sophisticated versions of Experience Accelerator engine, first virtual experience, first use by students
2014	Create an increasingly more complete and sophisticated engine, and tools to build virtual experiences	New versions of increasingly more capable engine with first set of prototype tools to create experiences
2015	Begin to transition EA into use at the DAU	Early deployment at DAU, increasingly more capable engine and tools, and learning assessments
2016 – 2018	Develop tools that enable a vibrant EA community for experience development and learning assessment	New experiences, increasingly more capable engine and tools, learning evaluations, deployment in marketplace community with suitable governance structure

The *Experience Accelerator* Project transition action plan and characterization are shown in Tables 5.4-12 and 5.4-13 below.

Table 5.4-12. *Experience Accelerator* Project Transition Actions

#	Transition Action	Principles Implemented
1	Worked closely with DAU to determine project concept and scope	• Plan Early
2	Delivered a number of Pilots for instructors and students, updating the Experience Accelerator based on detailed feedback	• Long and Short Term • Pilot Continuously
3	Created Experience Accelerator User Group to publicize results and provide feedback on development. Hold workshops at NDIA SE and INCOSE International Symposium conferences	• Engage Community
4	Develop tools to improve the capabilities of users to customize experiences for their use	• Productize

Table 5.4-13. *Experience Accelerator* Project Transition Plan

Characteristic	Evidence
Readiness (relevance, practicality)	• DAU desires the integration of the Experience Accelerator into their curriculum. The Experience Accelerator User Group is composed of 16 members from multiple organizations in the Federal Government, FFRDCs, industry and academia.
Progress (approval, adoption)	• The Experience Accelerator has undergone several instructor and student pilots which resulted in 140+ suggestions for improvement. Many of these have been incorporated into the Experience Accelerator and are now ready for use. The first set of tools have been developed and evaluated by external researchers. A workshop demonstrating these tools was conducted at INCOSE International Symposium 2015.

5.4.5 SYSTEMS ENGINEERING AND TECHNICAL LEADERSHIP EDUCATION PROGRAM

This research program primarily implements HCD strategies 2 and 3 – *Educate and Train Faster* and *Develop Effective Technical Leaders*. It currently includes two primary projects: the *Engineering Capstone Marketplace* Project and the *Technical Leadership* Project. The *Capstone* Project has mixed Core and US Special Operations Command funding. Even more extreme than the *Experience Acceleration* Program just described, all of the investment for the *Technical Leadership* Project has come from DAU – none has come from Core funding. Nevertheless, it is included here because it has been so critical to the HCD research effort.

Table 5.4-14 offers a description of these projects and which strategies they primarily support.

Table 5.4-14. Projects in the *Systems Engineering and Technical Leadership Education* Program

Projects	Started	Purpose	Primary HCD Supported Strategies
Engineering Capstone Marketplace	2010	Originally intended to show how to conduct multidisciplinary senior capstone projects in classical engineering programs, especially those that increase awareness of and appreciation for DoD applications. Building on its early success, the project has morphed into a marketplace where companies and government organizations can post on a website problems suitable for senior capstone projects. Students from multiple universities form teams to work on those projects under the supervision of faculty and the posting organization. Although small today, this marketplace model has the potential to scale nationwide, involving thousands of students in hundreds of projects and universities.	2,4
Technical Leadership	2010	Develop innovative ways to teach technical leadership to the DoD acquisition workforce, including not only systems engineers, but also others who must understand technical leadership, such as program managers. Iteratively pilot the resulting courses and integrate them into the DAU curriculum.	2,3,4

5.4.5.1 Engineering Capstone Marketplace Project

The *Engineering Capstone Marketplace (ECM)* Project is the evolution of research begun in 2010, which showed that a multidisciplinary senior capstone project could enhance development of systems SE competencies and increase interest in SE. *ECM* is now in its third year of matching engineering students working on their capstone or senior design with sponsors who provide challenging real world problems and dedicated mentors or subject matter experts. This matching is done through the *ECM* website[20]. Current efforts include development of the process and infrastructure to affordably scale this approach nationwide and improve how thousands of students are taught engineering across the US.

Sponsoring organizations from within the DoD have provided significant and challenging projects that have engaged engineering students from multiple engineering schools. The project sponsors provide funding for research, prototyping, testing, travel, etc., and a dedicated subject matter expert(s) to work with individual teams. These Capstone Marketplace projects provide an important opportunity for participating students to enhance their SE knowledge and experience by:

- Working on real and complex problems with engaged mentors
- Working on projects that require a multi-disciplinary team/approach
- Implementing and gaining experience with systems engineering approaches and processes.

Project sponsors have received many useful results. Several projects have led to follow on efforts and discussions have been initiated with the sponsor of two of these projects to develop field deployable devices.   These future engineers are entering the workforce with enhanced SE skills and understanding

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[20] See http://www.capstonemarketplace.org/.

that can help address the critical challenge of developing the next generation of SE talent for future DoD and defense industry needs.

Table 5.4-15 shows the focus and deliverables in the *ECM* Project through 2018.

Table 5.4-15. *Engineering Capstone Marketplace* Project Timeline

Year	Focus	Key Deliverables
Pre – Core	Develop and validate on a small scale approaches to fostering multidisciplinary senior capstone projects both within single universities and across universities, Research and develop a means to broaden participation in SE related Capstone Projects	Reports on how to foster multidisciplinary senior capstone projects, experience reports from participating universities, infrastructure to support nationwide expansion of the approach. A pilot web based marketplace for capstone engineering projects. Assessment of successful practices for managing multi-university, multi-disciplinary sponsored projects.
2014	Enhance and improve the *ECM* website to allow for broader participation and scale-up	Developed a more robust and scalable website for sponsors, faculty and students. Broadened sponsor and university participation, developed resources and project guidelines
2015	Redevelop the *ECM* website to enable project coordination and assessment tools. Increase outreach and communication with early adaptors to increase participation in the marketplace	New Capstone Marketplace website. Developed resources and documentation to disseminate information on *ECM* to government, industry, and academia. Develop SE learning assessment processes. Develop informational and/or instructional resources for implementation of SE into capstone projects.
2016 – 2018	Expand the Marketplace to draw hundreds of students from all across the country and across many universities, industrial and government organizations to sponsor multidisciplinary capstone problems	Robust infrastructure capable of supporting large-scale involvement of universities, students, and organizations, experience reports, outreach mechanisms to engage a nationwide audience of students, universities, and organizations, analysis of the value and impact of the Marketplace

The *ECM* Project transition action plan and characterization are shown in Tables 5.4-16 and 5.4-17.

Table 5.4-16. *Engineering Capstone Marketplace* Project Transition Actions

#	Transition Action	Principles Implemented
1	The transition of the *ECM* from an internal SERC capability to a stand-alone website that can be readily transitioned was part of the project goals which were refined in 2014. Steps that have been taken in the regard include; registration of a non-SERC domain name www.capstonemarketplace.org, outreach to the academic capstone design community, website redesign to reduce administrative load, development of web-site resources that better enable users to manage, plan, and conduct their projects.	• Plan Early • Long and Short Term • Productize
2	Outreach to both of the key national capstone project user groups have been conducted with participation and distribution of *ECM* literature at NDIA events, publication and presentation of a *ECM* paper and distribution of *ECM* literature at the 2015 American Society for Engineering Education (ASEE) conference. Various other efforts to engage government sponsors for *ECM* projects continues. Development of *ECM* project briefing materials is ongoing.	• Engage Community
3	Results of recently completed *ECM* student projects along are being assessed. Outreach to faculty advisors and sponsor liaisons to review results and determine lessons learned are ongoing.	• Pilot Continuously
4	A plan to develop online tools for the *ECM* website that will better enable dissemination of basic SE tools and processes and assessment of SE learning is being developed.	• Long and Short Term • Engage Community

Table 5.4-17. *Engineering Capstone Marketplace* Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• In the 2014-15 academic year, 9 of 10 student projects were successfully conducted by 4 academic institutions and 8 new student projects are underway in the 2015-2016 academic year. Both the sponsors and the faculty advisors have expressed interest or committed to continued participation.
Progress (approval, adoption)	• 2 conference papers have been published including a recent publication and presentation to the ASEE Design in Engineering Education Division. It is this group that is the most likely to adopt the *ECM* as a resource for faculty and students. This group has agreed to link the *ECM* to their Capstone Design Hub website and disseminate information on the *ECM* to its members. • The very successful participation of the Special Operations Forces (SOF) Acquisition, Technology & Logistics Science and Technology Office in the Capstone Marketplace was a prominent feature of 3 SOF/Industry roundtable discussions at the recent NDIA SOF Industry Conference.

5.4.5.2 Technical Leadership Project

The Technical Leadership Project began in 2010 to evaluate the hypothesis that the technical leadership capabilities of high potential, senior DoD systems engineers and technologists could be accelerated through an educational program in technical leadership. This research has resulted in the creation of an innovative approach to educating technical leaders through three lenses: systems, business, and enterprise. A series of three five-day courses have been prototyped, piloted and are in the process of

being transitioned to the DAU. Each course contains a series of independent readings, lectures, case studies, and student in-class exercises to accelerate systems technical leadership learning. The courses take the student from (a) leading systems development in the face of uncertainty and ambiguity to (b) understanding how commercial businesses or organizations accountable for multi-system and multi-customers strategize, operate and measure performance to (c) the technical leadership expectations of an enterprise senior technical leader responsible for assessing and adapting multi-nodal structural and activity-based processes within DoD or commercial enterprises.

Ongoing research supports the transition to the DAU of the three SYS 350 series Systems Engineering Technical Leadership prototype courses to address the need for technical leadership education in parallel with functional training. The transition approach includes (a) assignment of a DAU SYS 350 faculty instructional team; (b) SERC review, update, and refinement of the current prototype SYS 350A Systems, SYS 350B Business, and SYS 350C Enterprise technical leadership courses; and (c) two transition pilots for each of the three 350 series courses. Further, for each of the 350 A/B/C course pilots, the first of each A/B/C transition pilot will be led by the SERC research team and supported by the DAU Faculty team. The second transition pilot for each of the A/B/C transition pilots will be then be led by the DAU faculty team and supported by the SERC team as required.

Table 5.4-18 shows the focus, deliverables, and investment in the *Technical Leadership* Project through 2017, at which time it is likely to conclude.

Table 5.4-18. Technical Leadership Education Projects Timeline

Year	Focus	Key Deliverables	Core and Previous Investment
Pre – Core	Create and pilot three courses for the systems, business, and enterprise lenses	Course materials and reports from pilot classes	none
2014 – 2017	Refine the courses and integrate them into the DAU curriculum	Final versions of course materials for DAU-led pilots and for integration into the DAU curriculum; reports from pilot classes	none

The *Technical Leadership* Project transition action plan and characterization are shown in Tables 5.4-19 and 5.4-20 below.

Table 5.4-19. *Technical Leadership* Project Transition Actions

#	Transition Action	Principles Implemented
1	Engaged with DAU at onset of project to specify research outcome requirements so that the research results can be deployed at DAU. Developed transition plan with sponsors.	• Plan Early • Long and Short Term
2	Worked closely with DAU to develop relationship with Missile Defense Agency to provide an additional set of pilots and sites for broader adoption. Formed transition teams with sponsor.	• Engage Community

#	Transition Action	Principles Implemented
3	Developed and executing a continuous piloting process. Conducted nine pilots with feedback generated from over 5,200 faculty-student pilot contact hours.	• Pilot Continuously
4	Over 100 lecture, case study, exercise, simulations, and group project classroom segments were developed and tested.	• Productize

Table 5.4-20. *Technical Leadership* Project Transition Characterization

Characteristic	Evidence
Readiness (relevance, practicality)	• Both DAU and the Missile Defense Agency have piloted these courses and are seeking their transition from research into practice. The current research is focused on bringing about this transition.
Progress (approval, adoption)	• Conducted nine pilots with feedback generated from over 5,200 faculty-student pilot contact hours. The research task for 2016-2017 will result in these courses being taught by DoD instructors and formally integrated into DAU and the Missile Defense Agency.

5.4.6 HCD AREA NON-CORE FUNDED PROJECTS

During the time of the Technical Plan, the SERC has executed four non-Core-funded HCD Area projects as briefly described in Table 5.4-21 below. Additionally, one Core-funded project, *Helix*, received complementary funding from the Intelligence Community, and one project, *Experience Accelerator*, augmented its primary DAU funding with Core funds to improve automation to more quickly create new virtual experiences.

Table 5.4-21. HCD Area Non-Core Funded Projects

Project	Sponsor	Description
Science & Technology Portfolio Development	DAU	Develop, synthesize, and validate principles for formulating and executing a strategic plan for Science & Technology development, with the goal of enhancing the capability of the DoD's acquisition workforce.
Army Career Development Model	Army	Expand an earlier model for developing Army civilian systems engineers in the Army's Engineering Acquisition Career Field to assist in developing Lead and Chief Systems Engineers for Key Leader Positions.
Helix	IC	Expand the scope of research to understand differences between systems engineers in the defense community and those in commercial organizations and understand on which aspects of systems engineering should classic engineers be effective.
Experience Accelerator	DAU	Develop a capability to use simulation that is visceral enough to put the learner in an experiential, emotional state and effectively compress time and greatly accelerate the learning of a systems engineer faster than would occur naturally on the job.

Project	Sponsor	Description
Advanced Technical Leadership	DAU	Research, synthesize, and validate curriculum content and structure for future DoD systems engineering and technical leaders at the senior and executive levels.
Leadership Development Framework for the Technical Acquisition Workforce	DAU	Define a balanced career path structure for the DoD technical acquisition workforce that combines training, education, experiential learning, developmental assignments, and other elements leading to appropriate knowledge, skills and abilities suitable at each stage of a technical career.

5.5 INFRASTRUCTURE DEVELOPMENT

The SERC Vision states, in part, that at the end of this 5-Year plan:

• The SERC operates the world's largest and most-visited *SE Research Web site*, including the largest and best-organized SE Research experience base.

• It continues to provide leadership in evolving the SE Body of Knowledge.

• It runs the most widely attended and highest-rated SE Webcast series.

The SERC will develop the infrastructure that can be used by all of the research programs to support achieving these elements of the Vision. The strategy is to focus on two specific areas: the SERC Website and the SERC Innovation and Demonstration Lab. This work is scoped to be accomplished through a mix of SERC investment funds and Core funds.

5.5.1 SERC WEBSITE

The SERC website is intended to become the world's premier SE research website and researcher collaboration portal. As stated in the SERC vision, it is intended to become "the world's largest and most-visited SE Research website, including the largest and best-organized SE Research experience base". To support this objective, the SERC website was redesigned in 2014 and has regular changes, additions and improvements. Through a simple, clean, and intuitive web interface, site visitors can:

• Learn about the SERC;

• View news and events, not just SERC-related but those relevant to the entire SE community;

• Review and download current and historical SERC publications, including annual reports, technical plans, research papers, technical reports, and associated articles;

• View presentations from past SERC events, including SERC Sponsor Research Reviews and Doctoral Students Forums;

• Gain an understanding of SERC-affiliated programs, such as the SERC Doctoral Fellows Program; and

• With appropriate credentials, log in to the SERC Collaboration Portal, File Storage, and Product Distribution environment.

All of this functionality exists on the current SERC website with the exception of the collaboration portal, file storage, and product distribution environment. The remaining functions will be implemented in

concert with the development of the SIDL described in the next section. Initial operational capability of the portal is anticipated in 2016.

5.5.2 SERC INNOVATION AND DEMONSTRATION LAB (SIDL)

As mentioned earlier, one of the SERC's major goals for 2018 is to operate the world's largest and most-visited *SE Research Web site*, including the largest and best-organized SE Research experience base. Rather than strictly share written materials, the SERC will share its MPTs with the systems research community. The SIDL and the SERC Website will be the primary vehicles for these collaboration and sharing efforts.

The SIDL will be the first stop for an SE researcher. The virtual face of the facility will be integrated within the SERC website, effectively acting as a repository for the source code, executable files, data files, technical reports, white papers, and documentation developed and matured as part of SERC research. In addition, the site will contain a description of MPTs along with online demonstrations, videos, instructions, and downloads for SERC developed tools, open source tools, and URLs of often-used commercial tools. This material will be appropriately linked to the reports, papers, and other documentation relating to SERC sponsored research. At a future date, this may be linked to non-SERC sponsored SE research as well. Wikis and chat rooms will provide the means by which SE researchers can share their experiences with these tool sets. Another possibility for a SERC hosted and distributed tool is a Linux distribution packaged with all available open source SE tools that can run in this environment. This software could be made available as a downloadable "SE research starter kit." The SERC would provide expertise and assistance to SERC collaborating researchers to ensure that their research tools, data, and results are shareable on the SIDL.

The central physical facility is currently at Stevens Institute of Technology as an immersive environment in which SERC researchers can dynamically visualize their data, test hypotheses, develop appropriate algorithms and associated MPTs, and draw conclusions. The SIDL provides a means to "package" and "serve" demonstrations on demand, meaning that all configurations and settings are stored within the demonstration "package." So, when one demonstration requires specific settings in the Lab, it will not conflict with another demonstration's settings or lab configuration requirements. The facility consists of multiple vertically-mounted touchscreen displays along with the necessary computer hardware to run simulations and drive the graphical environment. Beyond the hardware and software, this lab is designed to provide multiple benefits to the SERC researchers and staff. The SIDL also provides a means for SERC researchers to collaborate remotely and "come together" in a lab environment. Additional physical facilities of various capabilities will be supported at other SERC collaborating institutions. These facilities will be supported by their host collaborating institutions but will provide an environment to demonstrate SERC research to interested parties near those sites.

The initial goal and pilot case of the SIDL, completed in July 2015, was to visually demonstrate three separate research projects and show how each of these research projects could be used collaboratively to produce results, which could not be achieved by the projects separately. While each of these research tasks provides significant capabilities and reveals valuable results on its own, the integration of the MPTs provides even greater capabilities and insights, and ultimately provides more valuable results to the SERC's sponsors.

6 NEW PROJECT INITIATION

There are numerous sources for new SERC projects. In many instances, the government sponsors have emerging critical problems that require the insights of research efforts. In these cases, an open call may be made to solicit proposals from within the SERC collaborator base to find the best research ideas. These are often reviewed by SERC leadership, the SERC Research Council, and the government sponsors. In other cases, the sponsor may have already identified leading researchers for the efforts who write a proposal for the work. In both approaches, the SERC strives to form collaborative teams when it is appropriate. The research community may develop research concepts that are presented to various federal sponsoring agencies, some of which may choose to sponsor the research. Each research program also develops new research topics that are related to their ongoing research efforts. Finally, the SERC has initiated a formal process of incubation grants to provide funding for SERC collaborators so that they can develop their research ideas to the point where formal proposals can be made. Research ideas from the incubation grants are described below.

As described in this Technical Plan, the SERC typically performs research on 20 to 25 active tasks simultaneously, exploring well-defined topics that are aligned with the SERC's research strategy. While it is believed that that the aforementioned research programs have a great potential to have a transformative impact on the DoD, IC, and beyond, there is a need to support new ideas in their infancy that may become critical research programs for emerging challenges. This "incubation" capability will be supported by an annual open call to the SERC research collaborating universities to propose early stage research that can be nurtured through relatively small levels of seed funding.

The initial open call took place in September 2014 with the objective of identifying and developing several short white papers outlining research programs with a significant potential to improve the practice of engineering systems. A total of 29 responses were received and reviewed with the sponsor and the Research Council. Of these, the following five proposals were selected and funded:

1. Mark Avnet, Texas A&M, *A Multilevel Framework of System Safety: Technical Failures, Human Factors, Organizational Culture, and Societal Influence*
2. LiGuo Huang, SMU, *Detecting and Evaluating Technical Debt of Software Systems*
3. Azad Madni, USC, *Formal Methods in Resilient Systems Design using a Flexible Contract Approach*
4. Kevin Sullivan, UVa, *Foundations of Systems Engineering*
5. Gary Witus, Wayne State, *Policies and Practices for Model-Centric Government-Industry Collaborative Environments for Systems Engineering and Development*

The results of these efforts will be considered for Core funding and potentially non-Core funding as well. The SERC incubator timeline is shown in Table 6.1-1.

Table 6.1-1. SERC Project Incubation Timeline

Year	Focus	Key Deliverables
Pre-Core	None – new start in 2014	
2014	Create proposal format and process in consultation with SERC sponsors with input from SERC collaborators	Announcement of incubator proposal solicitation to SERC collaborating universities
2015-2018	Selection of top proposals for funding	Award of seed funding to selected projects

ACRONYMS AND ABBREVIATIONS

ABET - Accreditation Board for Engineering and Technology

AIAA - The American Institute of Aeronautics and Astronautics

ASD(R&E) – Assistant Secretary of Defense for Research and Engineering

ASEE – American Society for Engineering Education

AWB – Analytic Workbench

BBP – Better Buying Power

BKCASE – Body of Knowledge and Curriculum to Advance Systems Engineering

CMU – Carnegie Mellon University

CONOPS or ConOps – Concept of Operations

CRADA – Cooperative Research and Development Agreement

CSER – Conference on Systems Engineering Research

DATASEM – Demonstration and Analysis Tool for Adaptive Systems Engineering Management

DAU – Defense Acquisition University

DoD – Department of Defense

DSL – Domain Specific Language

EA – Experience Accelerator

ECM – Engineering Capstone Marketplace

ERS – Engineered Resilient Systems

ESOS – Enterprises and Systems of Systems

FACT – Framework for Assessing Cost and Technology

FFRDC – Federally Funded Research and Development Center

FILA-SoS – Flexible and Intelligent Learning Architectures for Systems of Systems

GRCSE – Graduate Reference Curriculum for Systems Engineering

HCD – Human Capital Development

IC – Intelligence Community

IEEE-CS – Institute of Electrical and Electronics Engineers Computer Society

IMCSE – Interactive Model-Centric Systems Engineering

INCOSE – International Council on Systems Engineering

JHUAPL – Johns Hopkins University Applied Physics Lab

KSS – Kanban Scheduling System

MBSE – Model-Based Systems Engineering

MPT – Method, Process, and/or Tool

MS-SE – Masters Degree in Systems Engineering

NAVSEA – Naval Sea Systems Command

NCSOS – Net-Centric Systems of Systems

NDIA – National Defense Industrial Association

NIST - National Institute of Standards and Technology

NSWC – Naval Surface Warfare Center

OSD – Office of the Secretary of Defense

PhD-SE – Doctor of Philosophy Degree in Systems Engineering

PI – Principal Investigator

QSAM - Quantitative Schedule Acceleration Model

QTR – Quantitative Technical Risk

SE – Systems Engineering

SE&M – Systems Engineering and Management

SEBoK – Systems Engineering Body of Knowledge

SEEK – Systems Engineering Expert Knowledge

SEMT – Systems Engineering and Systems Management Transformation

SERC – Systems Engineering Research Center

SIDL – SERC Innovation and Demonstration Laboratory

SOF – Special Operations Forces

SoS – System of Systems

SoSE – System of Systems Engineering

SQ – System Qualities

STEM – Science, Technology, Engineering, and Math

SysML – Systems Modeling Language

TARDEC – Tank and Automotive Research, Development, and Engineering Center

TS – Trusted Systems

UARC – University Affiliated Research Center

USNWR – US News and World Report

USD(AT&L) – Undersecretary of Defense for Acquisition, Technology & Logistics